AN INVESTIGATION INTO COMPUTER AIDED INDUSTRIAL DESIGN IN RELATION TO DESIGN DEVELOPMENT

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Author Declaration

1 During the period of registered study during which this dissertation was prepared the author has not been registered for any other academic award or qualification.

2 The material included in this dissertation has not been submitted wholly or in part for any academic award or qualification other than for which it is now submitted.

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A Ph.D. thesis by

Hsueh-Shu, Liao

Abstract

The purpose of this study is to explore the interactions between designers and CAID systems. The different tools, including free hand drawing, 2D computer graphics, and 3D modelling, applied by designers in the design process were first investigated. Then the researcher explored the designers' mental processes in the 3D modelling of practical design episodes where design strategies were employed in Model Construction and Design Development tasks. To reflect a real situation in product design, actual design case studies, instead of laboratory experiments, were investigated. In this study, verbal protocol analysis was the major tool used to record the designer's mental processes in conducting the design tasks. The problems that were encountered by designers when interacting with the CAID systems were extracted and analysed in order to identify key points for the further development of CAID systems.

Finally, the researcher made suggestions for improvement and new functions to current CAID systems in the concluding chapters. The results of the experiments show that a CAID system should be compatible with human cognition and provide an interchangeable work model that will fit the Top Down and Bottom Up nature of designers' thinking processes. The differences between experienced designers and junior designers were also compared. The results indicate that experienced designers will apply design strategies less frequently than junior designers, which leads to a short design development time. Furthermore, experienced designers consider a lot more problem domains than junior designers do.

After organised the findings from this research for a new CAID system, an evaluation was conducted to refine the recommendations. Experienced designers' feedback was obtained through a questionnaire. The final conclusions for a new CAID system were obtained through considering the answers from experienced designers and a software engineer.

Key words: Computer-Aided Design (CAD), Computer-Aided Industrial Design (CAID), verbal protocol analysis, mental processing, and design development

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Chapter 1 Introduction

1.1 Background

Computer-aided-design techniques have been employed in product design and development for more than ten years. Design activities, with the impact of computer technology, have been transferred from traditional manual drafting to the computer based 2D drawing and 3D CAD systems. Computer techniques seem to have taken the place of the traditional design activity. In actuality, the three categories (traditional drafting, 2D computer graphics, and 3D-computer modelling) have been widely used together in the idea development stage.

In the beginning, the 2D-computer graphics were controlled by professional engineers using specific command strings. To make the computer graphic software more user friendly and to meet the requirements of the draftsman, icons were substituted for command lines. Moreover, the 3D computer-aided-design system was developed to show the design problems and details during the design process. In this way, it is easier for designers to expose the design solutions to the real context and refine the appearance and structure of a product. More importantly, they can control the quality of the design activity and enlarge the scope of their thinking and problem solving.

Such a design process, using different design tools, can be seen in the design department of the manufacturing companies, design houses, and design studios. In addition to the application of image processing, the 3D computer-aided-design system enables the designers to evaluate and explore the output of their ideas in advance. Virtual reality (VR) is another new field used to verify the utility of the design activity. The virtual context composed of visual, audio, and time elements makes it possible for designers to experience their proposals will be used in the real situation through a virtual interface (Lee, 1998; Robertson, 1994; Bhullar, 1997). The application of VR in the design process helps designers to correct the mistakes before a great amount of money and time is spent on the prototype. Finally, the CAM system, which is parallel to the CAD system, was developed to reduce the time for prototyping. With the CNC milling machines or rapid prototyping (RP) techniques, the CAM systems can embody the design proposal through file transformation and proper preparation of the 3D model. Designers can personally experience and evaluate their ideas in a shorter period of time. The integration of these design tools, not only accelerates the design processes, but also reduces the time span for product design and development.

The development of the CAD system application in Taiwan's industrial design sector has also combined the traditional drafting, 2D-computer graphics, and 3D-computer modelling. Different design tools and methods are used in accordance with the characteristics of the design stages. The industrial designers in Taiwan used to mainly apply AutoCAD to help with the drafting task and save time for revising and regenerating drawings. At this stage, designers benefited mostly from the use of computer-aided-drafting software. Then 2D-computer graphic software was developed and used for colour drawing and could be referred to as computer-aided-drawing. The 3D-computer system was not applied to the practical design activity until the early

1990s. Nowadays, there is a wide variety of CAD software for which the data entry and structure are significantly different. Of course, their utilities also vary. Though the situation of CAD systems is confusing, they have proved efficient and effective (Chen, 1998). However, industrial designers do not benefit from CAD systems in the idea development (the real situation will be discussed in Chapter 3.) CAD systems are only used in the later design stages to visualise designers' ideas but not in the design development stage (Elsas and Vergeest, 1998). The industrial design field is expecting a new CAD or CAID system that can provide an easier-to-use, more user-friendly environment and a more efficient way of problem solution, especially in the idea development stage.

1.2 Motivation

All the stages of product design and development are so closely tied with CAD/CAM systems that everything from design deployment to production ramp-up is dependent on the application of CAD systems. More importantly, product design databases, linked by the Internet, can help designers with the information retrieval and communication. The design process operates much more smoothly with this rapid information processing.

The CAD system designed for production prospers from 2D drafting software to3D electronic image processors. It not only accelerates the pace of engineering design, but also upgrades the precision degree of the design activity. 3D CAD software has been profoundly used in the product engineering design stage. In terms of the basic structure and interface design of the 3D CAD systems, they are generally considered to be suitable for the detailed design stage but not for the initial idea development stage (Elsas and Vergeest, 1998). This is due to the fact that there is too much uncertainty in the early stage of idea development. Because designers are not sure about the conditions, correct and sufficient data cannot be obtained. The CAD system, however, cannot do without the well-defined specification or space data. At the present time, the research of the CAD systems is in the initial position regarding the concept development stage of the industrial design field. The proper computer-aided idea development system is not mature enough to launch out commercially. Among so many areas, the researcher cares more about industrial design because of the researcher's professional background.

The research and development of so called computer-aided-industrial-design (CAID) has been undertaken for more than ten years. From early computer-aided drafting and drawing to the recent 3D modelling software, the efficiency of the CAID system has improved. Design and development of CAID can be categorised into the following groups:

(1) 2D computer graphic software for industrial design, including CorelDraw, Illustrator, PhotoShop, and AutoCAD. For example, Lien, T. J. at al. introduced a computer aided bicycle frame design with a 2D database, which was constructed using an AutoCAD modeller, and Auto LISP programs.

(2) 3D CAID systems such as electronic modellers. For example, the Fast Shape Designer, a surface modeller developed by Elsas and Vergeest, Delft University of Technology which is aimed to help designers with their idea development.

(3) 2D sketches transformed into 3D electronic modeller (Casper, 1995).

(4) Current database integration for idea development. The change of a parameter can change the generation algorithm and finally produce a series of patterns. For example, Mutator is applied in the shape generation of sculpture (Todd, Latham, and Hughes, 1991). Another concept is Shape Grammar, which is able to describe accurately larger classes of objects using a linear or visual vocabulary (Robin Baker, 1993).

(5) Using VR (Lee, 1998) to visualise the 3D model of the product and the interaction with the products or environment.

(6) Using Virtual gloves (Lin, 1997) to shape the form on screen.

All the research domains mentioned above are mainly aimed at generating visual electronic images in an easy and fast way. Namely, they are concerned about how to generate solid electronic image that is tangible through a user friendly interface and has reached their expected result to some degree. In this research, the researcher is interested in the way the computers can help designers with their idea development and help solve the initial design problem.

As far as this process is concerned, visual thinking (Arnheim, 1969) has been discussed and applied for years. It goes without saying that visual perception is the best channel the human being to get in touch with the outer world. In perceiving an object, people form a mental image in their mind. In the audition coloree' (colour hearing) experiment, Oakar Fishingr, Walter Ruttmann, and Norman McLaren (Arnheim, 1969) found that people's colour perception will be affected by music, in that visual perception will generate a non-mimetic image and make up the so-called synaesthesias. That is to say, the human's perception can also interpret audio stimuli visually. Visual processing is the main kind of the human information processing. As far as cognition is concerned, all mental operations involve the receiving, storing and processing of information are sensory perception, memory, thinking, and learning (Arnheim, 1969). In the design area, sketches have been used as a research medium for visual perception (Goel, 1995; Landay and Myers, 1995; Krame, 1994; Gross, 1996). In terms of cognitive psychology, designers' thinking and behaviours have been examined in two ways: (1) Same tasks are assigned to expert and naive designers to explore their difference in problem solving (Suwa and Tversky, 1997)), and (2) different tasks are assigned to designers to examine the strategy and thinking procedure they use in problem solving (Mc Neill and Edmonds, 1994). Though these studies belong to different domains, they focus on the conceptual development stage. The conceptual design process itself can be considered as the one in which the designer navigates through an abstract problem domain and employs various strategies to elaborate the problem description (Simon, 1981; Gero, 1992). In order to give a rich representation of the design process, a distinction is made between the designer's place in the problem domain and the strategies used by the designer during the design process.

The designer's navigation through the problem domain can be represented in two orthogonal dimensions (Gero and Mc Neill, 1998). The first dimension, covering function, behaviour and structure are derived from a model of design reasoning (Gero and Rosenman, 1990). In such a dimension, *function* relates to the purpose of an artefact; *behaviour* relates to the actions or process of an object or artefact. Reasoning in *structure* involves the manipulation of objects or their relations to bring about a physical solution. Reasoning with function, behaviour and structure can be differentiated for any design episode (task) independently of the design problem although the actual categorisation is dependent on the specific design problem. The second dimension divides the problem domain into a number of levels of abstraction. The designer's attention shifts from high level overall views of the problem down to consideration of low-level details of the problem.

The design process can be viewed as one in which the designer engages the design problem by calling upon a repertoire of micro strategies. The micro strategies are self-contained and relate to the current state of the process. Identifying similar actions and creating a list of the repertoire used during the design task can form a rich representation of the designer's actions. Classifying the micro strategies into a small number of groups can further enrich the representation. The number of different micro strategies that can be identified in a design process is dependent on both the designer's experience and on the complexity of the problem.

In addition to identifying micro strategies, the designer's approach can be viewed in the longer term with the designer executing a long-term plan or macro strategy. The macro strategy dimension adds richness to the representation by adding context to the micro strategies.

It is, however, the question whether or not the involvement of a design tool such as CAID causes changes in the industrial designers' idea generation and development. Do designers depend upon only their visual perception to develop and refine their ideas during the designing activities, especially in the idea development stage? It is necessary for us to investigate the micro strategies and macro strategies which designers adopt in the application of CAID tools. Do they still need other models to proceed with their idea development? How will such CAID designing activities be effectively improved? In their study of idea development of mechanical design, Hondal and Alangholtz (1992) used C language to build up product defining data (PDD), product describing model (PDM), and solution data base (SDB). In the window operating system, the CAD system made it possible for designers to generate a variety of ideas that could be evaluated and refined in later stages. Though it was a study regarding product functional design, the behaviour model of the idea development is similar to that of industrial design. The research indicated that there is a close tie between the user interface and the human being's problem-solving model. In the process, the entry data, design message of the command, and the way designers interact with the system can be looked upon as a way of information processing, which prevails in people's everyday life (Wickens, 1992). The study focused upon how designers could be helped to develop ideas and solve problems through computer technology. Compared with the generation of the visual image, the providing this help is more ambitious in terms of its approach and objectives. Consequently, the issue of how CAD systems will help industrial designers in idea development needs to be further studied. The researcher needs to explore how designers interact with the CAD systems. Particularly, it is important that the researcher investigates the relationship between the designers' thinking model and the use of the CAD systems from which the performance of design activity can be improved. From the research, designers' information perception and processing can be explored and used as basis for developing the CAID software in the near future.

1.3 Aims and objectives

The purpose of this study is to understand how designers apply CAD systems to their idea development. The researcher attempts to extract factors that will help CAD software engineers better meet the using of industrial designers in the design development stage.

This study also attempts to explore designers' thinking processes during the idea development stage. However, special emphasis is placed upon the difference in idea development and the use of CAD systems.

The specific objectives of the study are listed as follows:

(1) To review and understand how industrial designers apply CAD systems in design activities, especially in idea development?

(2) To compare and contrast different CAID systems.

(3) To verify the difference and utility in using different tools, i.e. free hand drawing, 2D-computer drawing and 3D computer modelling.

(4) To develop an experiment to identify the discrepancies of idea development between using traditional tools and the modern CAID systems based techniques.

(5) To discuss the designer's way of thinking in using CAID systems for idea development.

(6) To draw conclusions and recommendations for further study.

1.4 Research framework

The researcher has been working as an industrial designer for more than 16 years, and is very interested in the creative activity of the design process. The scope of research in the study, therefore, is limited to idea development in industrial design.

Idea development plays a key role in the design development process and can be considered as the core of the design activity. The purpose of all design activities in the early stage, from the initial marketing research, design problem definition to design objective identification, most of which are verbal descriptions of the design problem, is to determine the correct direction for idea development. Idea development is the indispensable process to transform the abstract description into a feasible solution. Therefore, the data collection, analysis, and synthesis, in the early stages, or the prototyping and mass production in the later stages, should be interpreted and explored by way of idea development so as to propose design solutions that meet the requirements of the design objective. This is one of the reasons why the researcher places so much emphasis on the idea development stage of the industrial design area.

Moreover, many researchers have pinpointed that the use of CAD systems has deeply influenced traditional design methods and tools (Medland and Mulline, 1988; Coticchia, et al, 1993). In other words, CAD systems that have been involved in the design process might have greatly affected the native of idea development. In the past, psychologists have done research on the thinking model of artists and designers. The impact of CAD systems upon industrial designers' idea development, however, is rarely explored. More attention needs to be paid to this issue. The author will attempt to explore this issue in the following stages (Figure 1.1):

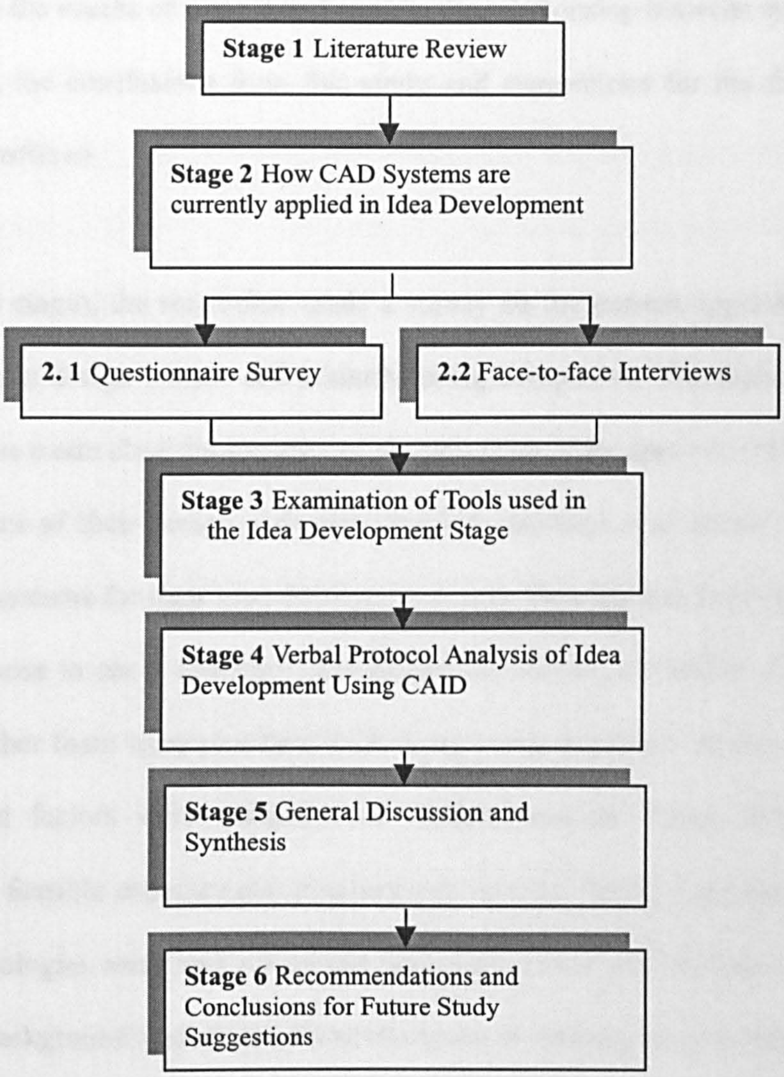

Figure 1.1 The flow chart of research framework

Stage 1: Literature review of CAD systems and idea development process.

Stage 2: Make a survey of the current CAD applications in the design activity of industrial designers.

Stage 3: Compare of the difference between traditional design tools and CAD systems in industrial designers' idea development.

Stage 4: Based upon the result of Stage 3, infer a suitable research framework for CAD system for design development. Using such a model will perform a verbal protocol study.

Stage 5: Analyse the results of stage 4 and explore the relationship between stages.

Stage 6: Finally, the conclusions from this study and suggestions for the future work will be offered.

At the early stages, the researcher made a survey on the current application status of CAD systems in design houses and manufacturing companies. The management of the design process made clear the strategy of the procedure they apply to CAD systems and characteristics of their design activities. Special emphasis was placed upon how they used CAD systems for their idea development, how they applied the CAD system, and why they chose to use a specific CAD system. Moreover, the utility of the CAD system and whether there were problems with it were also explored. At this stage, the above mentioned factors were extracted for further research. These factors lay a foundation for a feasible experimental measurement in later stages. Last but not least, different methodologies and results from the literature review provided the researcher with sufficient background knowledge about the issue. A research framework was then proposed for the study of idea development.

With the understanding of the current application status and characteristics of CAD systems, the researcher studied the effects of CAD systems used on the idea development stage. A verbal protocol analysis method was then performed to verify the validity of the research methodology. In most design activities, designers use both traditional tools and CAD systems. Properly observed and tested, the difference of the usage of these design tools can be identified. Furthermore, a rough idea about how the design tools support designers' idea development can be derived.

With the results from Stage 2 and Stage 3, the research framework and methodology will thereby be specified. The framework is composed of the research content and procedure. Meanwhile, the analysis items were determined to verify the reliability for later protocol experiment. After the verbal protocol is finished and analysed in the stage 4, a general discussion and synthesis will proceed to assess the possible solution for CAID systems engineers and industrial designers using the CAID systems and to examine the results of stage 4. Finally the relationship between design tools and idea development was explored in comparison with the results of those study stages. The study ends with the conclusions and future work suggestions.

1.5 Methodology

A questionnaire was designed and mailed to design companies in Stage 2 to survey the current status of CAD system application. Through the questionnaire survey, the researcher attempted to achieve the following goals:

(1) Determine how CAD systems were perceived in the needed industrial design profession.

(2) Identify the different CAD systems used in idea development.

(3) Identify features of CAD systems and the reasons why they chose such CAD systems.

(4) Record the experience and evaluation of the CAD systems being used.

Typical CAD systems and design companies that had long used the system or were thinking of applying CAD systems in idea development would be chosen for further research. Face-to-face interviews were performed to make clear the way that CAD systems supported idea development and details in application. From design case, designers would be encouraged to explain their reasons in the update of the hardware and CAD systems with a greater breadth view. Furthermore, the effect CAD systems had on the outcome of design as well as the related changes in design procedure would be obtained.

After the previous stage, verbal protocols were the major method to explore the designers' interaction with CAD systems. The verbal protocol analysis was introduced by the *thinking aloud* method first described by Ericsson and Simon (1993), and further developed by Van Someren et al (1994). In 1998, Gero and Mc Neill analysed this method in depth and made it a useful tool in design research to investigate how designers conducted their design activities. Protocol data was very rich but unstructured. In order to obtain a detailed understanding of design processes, it was necessary to project a framework on the related data. This framework was derived both from direct observation of the designer's interaction with the problem domain and from models of design reasoning.

The recording unit of the designer's activities was called a *segment*. Van Someren et al. described a process of aggregating segments into design tasks. The method focused on designer's actions or intentions. The protocol was divided according to the designer's intention that was interpreted for each segment. A change in intention flagged the start of a new segment. Each segment comprises of the time, problem domain (reasoning the function, behaviour and structure), dialogue and actions. After recording the designer's activities (protocols) following the sequential segment, a coding execution was adopted. The coding scheme was allowed to evolve during the analysis. As segments were identified that do not fall neatly into the existing scheme, a new category would be introduced or an existing category was redefined.

By comparing the results achieved at each stage in the coding process, it was possible to assess the robustness of the approach and to identify areas within the approach that might be improved. It could also be used to give an indication of the validity of the results. The consistency of the coding method was assessed by comparing each of the protocols with each other to establish the level of agreement between protocols.

For each of the protocols the results of the coding were recorded on a single graph. Each of the coding dimensions was marked against time. This included the time axis that represents the segment lengths in the context of the overall design task. The articulation among categories could be visualised by these graphs. And this provided the opportunity to have a much more detailed analysis of the behaviour of designers by aggregation and analysing these 'raw' results. The results would be further explored using graphical and filtering techniques to represent the results. According to these results, a design process 'signature' could be used to categorise designing styles. The verbal protocol analysis method provided the basis for articulating different aspects of the behaviour of individual designers with the different tools to aid design.

In Stages 3 and 4, verbal protocols (Ericsson and Simon, 1993; Someren et al., 1994) was performed to explore different issues. In Stage 3, different design tools was used to help designers conduct their idea development. Subjects were then assigned to different groups in accordance with the design tools. Verbal statements and sketches of the subjects were used as the research medium, from which how designers applied these design tools were determined. Because it took lots of time, an appropriate number of subjects would be selected. In addition to the subjects' verbal description, special attention was paid to how the subjects dealt with information. As mentioned earlier, information processing was a daily routine for human beings. During the idea development stage, the information transmission, retrieval, analysis, and so on was the message the researcher was concerned with. In the information era, computers and information almost meant the same thing. For example, information technology or information communication depended on computer technology. Information communication played an important role in computation technology. Since idea development was filled with message and computers were used to support the design activity, information became the most important factor. Texts, pictures, numerical data, symbols, sounds, and images generated in the thinking process could be considered as messages. In other words, all the things that could be perceived by human being were considered as valid information. With video film, the subjects' behaviour information could be cross-examined and analysed. Because the researcher focused on the designer's design processing rather than the results of design, the designer's sketches 2D computer drawings and 3D models were not emphasised to analyse at this stage. Stage 4 also employed verbal protocol as an experimental method. Items of a checklist would be examined to verify the reliability of the methodology according to the results in earlier stages. The checklist covered the following five items:

(1) Evaluation of the CAD system and peripherals. Was the CAD software suitable for idea development? Was the hardware equipped with sufficient calculation speed and memory? Did the hardware and software help designers undertake the design activity smoothly?

(2) Verification of the test data. Was it necessary to change the format of the user interface elements such as the design aim, design objectives, industrial limitation, and product catalogue? How to minimise the influence of experimental procedure, i.e. video and documentation way of data recording?

(3) Verification of the experimental tasks. Different tasks would affect the subjects' levels and functions of the thinking process. The contents of experimental tasks should be adjusted to obtain more reliable results.

(4) The control of the task time. Verbal protocol took much more time than other experiments. To reduce the subjects' mental and physical burden, on one hand, a proper amount of task time was indispensable. On the other hand, a sufficient number of messages were necessary for the researcher to analyse the data. The number of subjects in this stage, therefore, should be bigger than the earlier stages.

(5) Adjustment of the measurement scope. The measurement range would be verified to check if it was too wide or too narrow. Some in-depth aspects would be focused in later analysis of the test data.

The results obtained in these stages would be compared with those of other research. Through discussions of the results, the researcher would make the conclusions and suggestions for future work.

Chapter 2 Literature Review

2.1 Introduction

In accordance with the research framework and content mentioned in Chapter 1, the researcher gathered related information to explore the state of the art of CAID systems. First of all, the definition, professional domain, and procedures of industrial design were delineated. The procedure and content of the design activities in idea development were examined. Finally, the relationship between designers' thinking processes and cognitive psychology was also addressed.

Another key issue dealt with the application of CAID technology and the problems in the development of sequential activities in industrial design. From 2D graphics to 3D wire-frame visual representation, CAD systems make it possible for designers to visualise the surface features of 3D models in the way of ray tracing. Furthermore, the functions of lighting and texture can be specified. The development of CAD technology allows the creation of a digital image at a photo-realistic level. With their powerful functions, 3D CAD systems have become an indispensable tool in design and art. In the field of industrial design, Buckner (1993) used Alias 3D software to demonstrate how to apply CAD systems to product design. Though CAID systems have already proved to be successful (Harkins, 1994; Iwao, 1998; Lennings, 1992), many researchers are working hard to enhance the user friendliness of CAID systems to meet the characteristics of the design activity. Such CAID systems not only uplift design quality and speed up the development of product design, but also reduce the errors in design. Some scholars, for example, Elas and Vergeest (1995) and Van Dijk and Casper (1992), focus upon how to construct 3D models more effectively, while others try to combine mathematical algorithm and cell library to generate design alternatives in which designers can have more choices (Chang, 1998; Cheng, 1995; Lee, 1998; Yujin, 1998). Other researchers have tried to determine the characteristics of designers' thinking process. Most of them have used verbal protocol to investigate this problem (Gero and McNeil, 1998; Landay, 1995; Suwa and Tversky, 1997).

Most researchers claim that the CAID systems, whether they are already commercialised or still in development, should recognize the characteristics of the designers' way of thinking. Meanwhile, the methods designers' use in idea generation may be applied to CAID systems to help designers with their creativity and generate a variety of ideas. In this chapter, emphasis is placed upon examining the problems designers have in using CAID systems. Factors that are closely related to the application of CAID systems can then be extracted and analysed in order to improve CAID systems and their use.

2.2 The Idea Development Process of Industrial Design

2.2.1 Industrial Design

Industrial design is a creative, inventive, and iterative process separated from the means of production. It involves an eventual synthesis of contributory and often conflicting factors into a concept of three-dimensional form, and its material reality, capable of multiple reproduction by mechanical means. It is thus specifically linked to the development of industrialisation and mechanisation that began with the Industrial Revolution in Britain around 1779, though it cannot be described simply as a deterministic product of those events. Its distinguishing characteristic, the separation of design from the processes of making, in fact emerged before the Industrial Revolution, with the evolution from the late medieval period onwards of early capitalist industrial organisations based on the craft methods of production (Heskett, 1980).

In the early 1900's, several German companies, including AEG, a large electrical manufacturer, commissioned a multitude of craftsmen and architects to design various products for manufacture. Initially, these early European designers had little direct impact on industry; however, their work resulted in lasting theories that have influenced and shaped what is today known as industrial design. Early European theories on Industrial Design (ID), such as the Bauhaus movement, went beyond mere functionalism; they emphasised the importance of geometry, precision, simplicity, and economy in the design of products. In short, early European designers believed that a product should be designed "from the inside out" and form should follow function (Lorenz, 1986).

Today, the Industrial Designers Society of America (IDSA) defines industrial design as the "professional service of creating and developing concepts and specifications that optimise the function, value and appearance of products and systems for the mutual benefit of both user and manufacturer." This definition is broad enough to include the activities of the entire product development team. In fact, industrial designers focus their attention upon the form and user interaction of products. Dreyfuss (1967) lists five critical goals to achieve to help a team of industrial designers when developing new products:

(1) *Utility:* The product's human interfaces should be safe, easy to use, and intuitive. Each feature should be shaped so that it communicates its function to the user.

(2) Appearance: Form, line, proportion, and colour are used to integrate the product into a pleasing whole.

(3) Ease of maintenance: Products must also be designed to communicate how they are to be maintained and repaired.

(4) Low costs: Form and features have a large impact on tooling and production costs, so these must be considered jointly by the team.

(5) Communication: Product designs should communicate the corporate design philosophy and mission through the visual qualities of the products.

Ulrich and Eppinger (1995) asserted that a convenient means for assessing the importance of ID to a particular product is to characterise importance along two dimensions: ergonomics and aesthetics.

(1) Ergonomic needs

(1a) *Ease of use.* For frequently used products, such as an office photocopier, or for infrequently used products such as a security ladder, ease of use seems to be extremely important. Ease of use is more important if the product has multiple features and/or modes of operation, which may confuse or frustrate the user.

(1b) *Ease of maintenance.* If the product needs to be serviced or repaired frequently, then ease of maintenance is crucial. The features of the product need to communicate maintenance/repair procedures to the user.

(1c) *The interactions between users and the products.* In general, the more interaction users have with the product, the more the success of the product will depend on ID. Furthermore, each interaction may require a different design approach and/or additional research.

(1d) *The novelty of the user interaction.* A user interface requiring incremental improvements to an existing design will be relatively straightforward to design. A more novel user interface may require substantial research and feasibility studies.

(1e) *The safety issues.* All products have safety considerations. For some products, these can present significant challenges to the design team. For example, the safety concerns in the design of a child's toy are much more prominent than those for a new computer mouse.

(2) Aesthetic needs

(2a) *Product differentiation.* Products with stable markets and technology are highly dependent upon ID to create aesthetic appeal and, hence, differentiation. In contrast, a product such as a computer's internal disk drive, which is differentiated by its technology, is less dependent on ID.

(2b) *The pride of ownership, images, and fashion.* A customer's perception of a product is in part based upon its aesthetic appeal. An attractive product may be associated with high fashion and image and will likely create a strong sense of pride among its owners.

(2c) *An aesthetic product will motivate the team.* A product that is aesthetically appealing can generate a sense of "team pride" among the design and manufacturing staff. Team pride helps to motivate and unify everyone associated with the project.

Most industrial designers follow an established procedure for designing the aesthetics and ergonomics of a product. Although this approach may vary depending on the firm and the nature of the project, industrial designers generate multiple concepts and then work with engineers to narrow these options down through a series of evaluation steps. Ulrich and Eppinger (1995) also pointed out generic ID processes made up of the following phases:

(1) Investigation of customer needs

Since industrial designers are skilled at recognising issues involving user interactions, ID involvement is crucial in the need definition process. While the involvement of marketing, engineering, and ID certainly leads to a common, comprehensive understanding of customer needs for the whole team, it allows the industrial designer in particular to gain an intimate understanding of the interactions between the user and the product.

(2) Conceptualisation

Once the customer needs and constraints are understood, the industrial designers help the team to conceptualise the product. During the concept generation stage engineers naturally focus their attention upon finding solutions to the technical sub-functions of the product. At this time, the industrial designers concentrate upon creating the product's form and user interfaces. Industrial designers make simple sketches, known as thumbnail sketches, of each concept. These sketches are a fast and inexpensive medium for expressing ideas and evaluating possibilities. The proposed concepts may then be matched and combined with the technical solutions under exploration. Concepts are grouped and evaluated by the team according to the customer needs, technical feasibility, cost, and manufacturing considerations.

(3) Preliminary Refinement

In the preliminary refinement phase, industrial designers build models of the most promising concepts. *Soft models* are typically made in full scale using foam or foamcore board. They are the second fastest method — only slightly slower than sketches — used to evaluate concepts.

(4) Further Refinement and Final Concept Selection

At this stage, industrial designers often revert from soft models and sketches to hard models and information-intensive drawings that are known as *renderings*. Renderings show the details of the design and often depict the product in use. Drawn in two or three dimensions, they convey a great deal of information about the product. Renderings are often used for colour studies and for testing the customers' reception to the proposed product's features and functionality. The final refinement step before selecting a concept is to create hard models, alluded to previously. These models are still technically non-functional, yet are close replicas of the final design. Hard models can be used to gain additional customer feedback in focus groups, to advertise and promote the product at trade shows, to sell the concept to senior management within an organisation, and to further refine the final concept.

(5) Control Drawings

Industrial designers complete their development process by making control drawings of the final concept. Control drawings document functionality, features, sizes, colours, surface finishes, and keys dimensions. Although they are not detailed part drawings, they can be used to fabricate final design models and other prototypes. Typically, these drawings are given to the detailed part designers for completion.

(6) Co-ordination with engineering, manufacturing, and external vendors

The industrial designers must continue to work closely with engineering and manufacturing personnel throughout the subsequent product development process. Some companies now even use industrial design consulting firms that often offer comprehensive engineering services, including detail design and the selection and management of outside vendors of materials, tooling, or components, as well as manufacturers, who perform the final assembly of the product.

Not only should Industrial designer be concerned with the ergonomics and aesthetics of a product, but they also need to work with engineers to narrow down the discrepancies between the ideation and engineering issues.

2.2.2 Idea Development in Industrial Design

Ulrich and Eppinger (1995) claimed that industrial design is incorporated into the overall product development process at any time during a development programme. The phases of the product development process are composed of five stages: identification of customer needs, concept generation and selection, system-level design, detail, testing and refinement, and production ramp-up and launch. The timing of ID effort depends upon the nature of the product being designed. They classify products according to the nature of the dominant challenges facing the development team: achieving technological performance, designing the exterior and user interfaces, or both. The classifications are technology-driven products, user-driven products and technology-and-user-driven products (Figure 2.1).

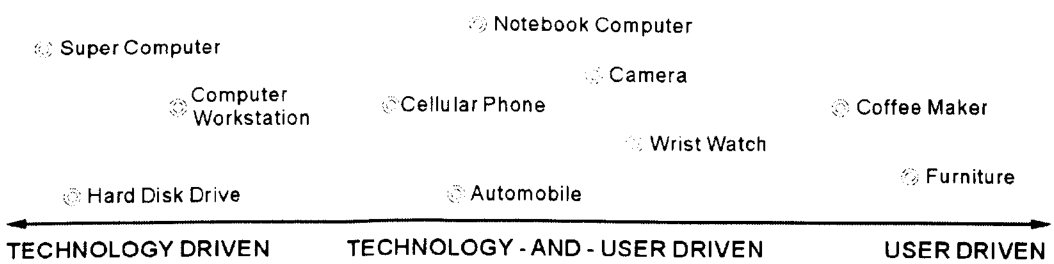

Figure 2.1: The classification of some common products on the continuum from technology-driven product to user-driven product

Typically, ID is incorporated into the product development process during the later phases for a technology-driven product, during the earlier phases for a technology-and –

user-driven product, and throughout the entire product development process for a user-driven product. Figure 2.2 illustrates these timing differences. Note that the ID process is a sub-process of the product development processes; it is parallel but not separate. As shown in Figure 2.2, the ID process described above may be related to the overall development process. The technical nature of the problems that confront engineers in their design activities typically demand substantially more development effort than the issues considered by industrial designers. In other words, the idea development of industrial design starts at the identification of customer needs and ends at idea refinement.

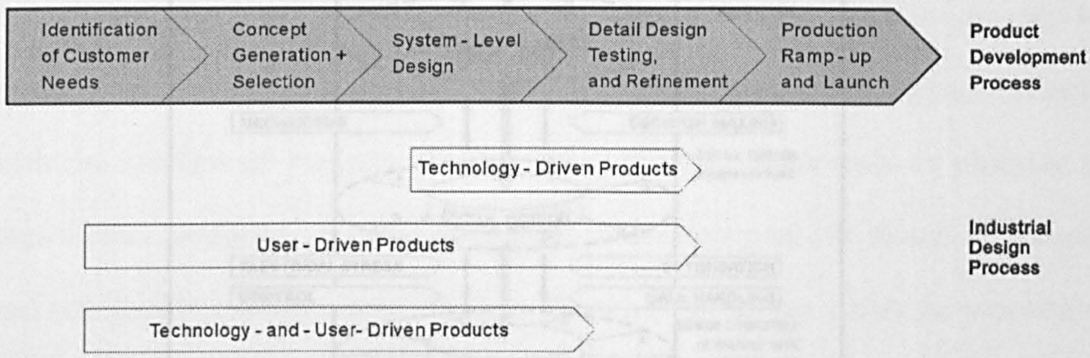

Figure 2.2: Relative timing of the industrial design process for three types of products

Gruenwald (1992) states that the product development process and industrial design process should start at the market opportunity by searching, exploring and analysing the sales, competitors, customers, basic technologies and other factors, which will influence the success of products. He also asserts that the creative process is based on a selective assembly of information. It's not a mere playback; its execution communicates something. In the commercial world, it must express and fulfil a latent or at least a perceived real desire. It is based on knowledge that leads to new product ideation from diverse sources. It is organised through re-assembly, through simplification, through a penetrating grasp of the obvious – which may have escaped the designers' attention. He asserted that the rearrangement of information makes designers look at targets with a different point of view to discover new solutions.

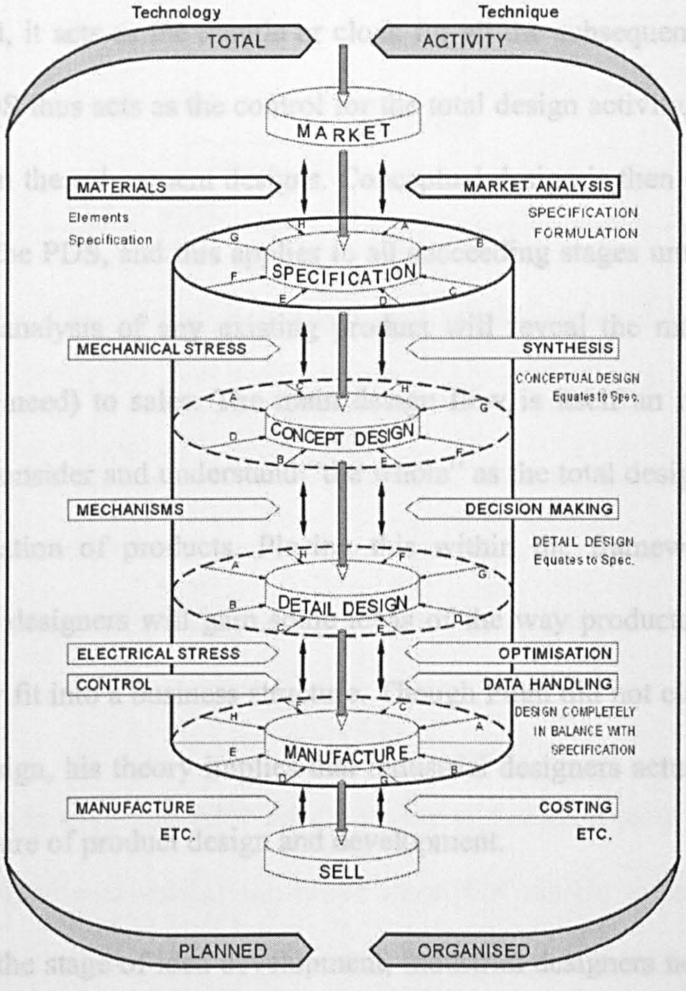

Figure 2.3: The total design activity model

In terms of the procedure of product design and development, Pugh (1982, 1990) proposed a total design activity model that can be constructed as having a central core of activities, all of, which are imperative for any design, irrespective of domain. Briefly, the design core consists of market (user need), product design specification, conceptual design, detail design, manufacture and sales (Figure 2.3). All design starts with a need that, when satisfied, will fit into an existing market or create a market of its own. From the statement of the need — often called the brief — a product design specification (PDS) must be formulated — the specification of the product to be designed. Once this is established, it acts as the mantle or cloak for all the subsequent stages in the design core. The PDS thus acts as the control for the total design activity, because it places the boundaries on the subsequent designs. Conceptual design is then carried out within the envelope of the PDS, and this applies to all succeeding stages until the end of the core activity. An analysis of any existing product will reveal the main design flow from market (user need) to sales. The main design flow is itself an iterative process. It is essential to consider and understand "the whole" as the total design package concerned with the creation of products. Placing this within the framework of planning and organisation, designers will gain some ideas of the way products should be designed, and how they fit into a business structure. Though Pugh did not clarify the procedure of industrial design, his theory implies that industrial designers actually participate in the entire procedure of product design and development.

During the stage of idea development, industrial designers need creativity, both in product aesthetics and interface design. Baxter (1995) professed that creativity is at the heart of design, at all stages throughout the design process. From the psychologist's point of view, creativity is not claimed to be completely understood. But there is enough knowledge to signpost the route to creativity and to describe some characteristics of the main landmarks along that route. Baxter has described a stairway to creativity (Figure 2.4) which is a structured way of presenting a common sense understanding of creativity. The first insight is the way one frames in one's mind the need for some creative discovery. Most inventors, and nearly all the great scientists, artists and technologists are highly focused on one type of problem. Their first insight frames the problem in one area and focuses their mind on that problem until they solve it.

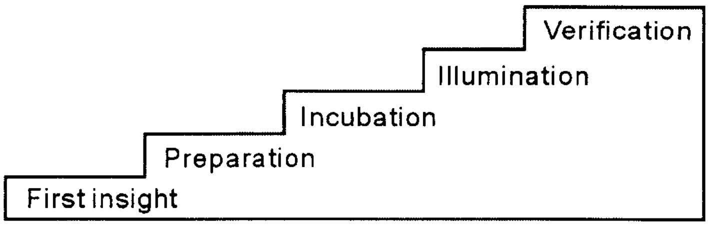

Figure 2.4: The stairway to creativity (Originally proposed by Wallas, 1926)

From research of accounts of great discoveries, and from the practical experience of more ordinary mortals, it has become clear that the key to creative thinking is preparation. A creative idea is generally a connection, an expansion or a perception in a new light, of a set of existing ideas. Preparation is the process by which the mind becomes immersed in these existing ideas.

First insight and preparation are the logical and rational parts of creativity. It makes sense that a creative breakthrough needs some first insight to frame the problem and establish a goal. It then makes sense that an understanding of current knowledge is required in order to advance beyond that knowledge. The next stage of how to actually make that creative breakthrough seems more to do with luck, inspiration or, as many scientists and artists have suggested, divine intervention. It certainly seems to have little to do with logic and rationality. Arthur Koestler goes on to describe how bisociation may be the key to creativity. A creative breakthrough is very often the association of two known ideas or principles that have not been connected previously. We can think of our brains as devices for making associations. When we see an object, we associate it with words (what is the object called), with memories (when did we see it last), with emotions (how did we feel when we saw it last) and we associate it with the object's basic significance to our lives (can we eat it, have sex with it or should we run away in terror from it). All of our perceptions, thoughts, emotions and memories are filed away in little networks designed to provide the most useful associations for going about our daily lives.

Therefore, creative thinking can make a breakthrough to the design problem. Creativity is brought forth by a continuous derivation, and creative thinking has much to do with idea generation. Idea generation is at the heart of creative thinking (Baxter, 1995). The ideas produced are the lifeblood of the creative process. They are what put the "creative" into creative thinking. We have already seen that truly creative inspiration is often the result of bisociative thinking, the joining together of previously unrelated ideas. Many idea generation techniques try to force participants to make these unlikely connections. These methods are criticised by more rationally and literally minded people as being "wacky" and "grasping at straws". This is true and often they do not work. But bisociative thinking is intrinsically difficult and we have yet to discover sure-fire ways of achieving it. Most idea generating techniques, to their credit, require little time and effort.

Baxter (1995) introduces three main categories of techniques for the creative generation of ideas (Figure 2.5).

- Problem reduction techniques examine the component parts, features and functions of the problem and attempt to solve that problem by modifying one or more of them.

The techniques are reductionist because they look only at the existing characteristics of a product and do not look beyond the product of its solution.

- Problem expansion techniques look beyond the immediate domain of the problem for inspiration. Problem expansion is primarily a way of broadening the perspective on a problem and thereby opening up a wider range of potential solutions.

- Problem digression moves away from the problem domain for inspiration and is totally concerned with lateral thinking. Some techniques begin with the original problem and use digressive methods to stimulate lateral thinking outwards from the problem. Others start with a totally unrelated stimulus and try to work from their back to the problem, thereby stimulating lateral thinking in the process.

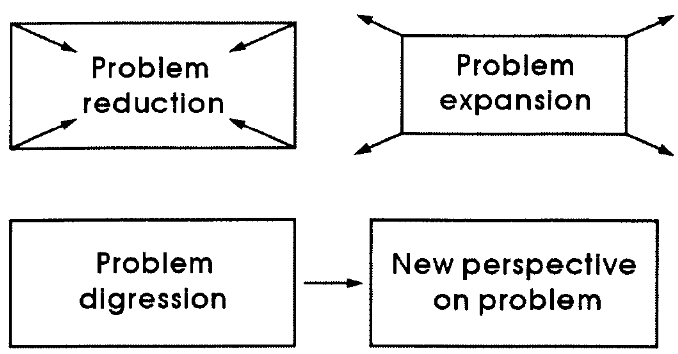

Figure 2.5: The main categories of creative idea generation techniques (Baxter, 1995)

He also states six different methods for generating ideas. These methods are presented below:

- Product analysis starts with an existing product and systematically arranges its functions in a hierarchy. This forces a designer to work out what is the primary function of that product and how the subsidiary functions contribute to the main function (Figure 2.6).

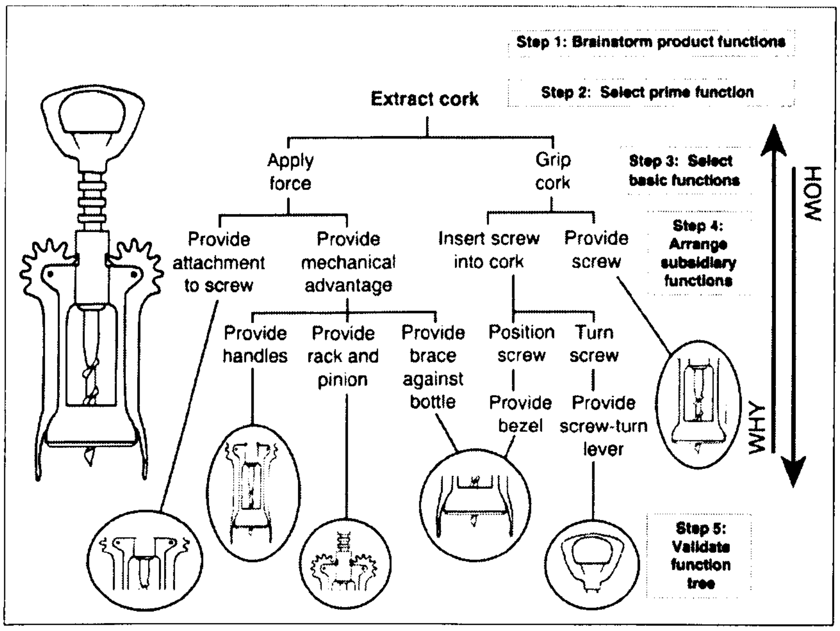

Figure 2.6: The product function tree for a corkscrew (Baxter, 1995)

- Product feature permutation also starts with an existing product and explores all the different ways in which its components or elements can be arranged. This technique is also used for problem reduction, and it plays a key role in embodiment design (Figure 2.7, Figure 2.8).

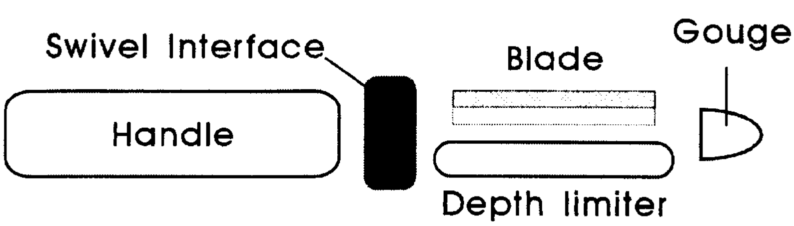

Figure 2.7: The feature abstraction for a potato peeler (Baxter, 1995)

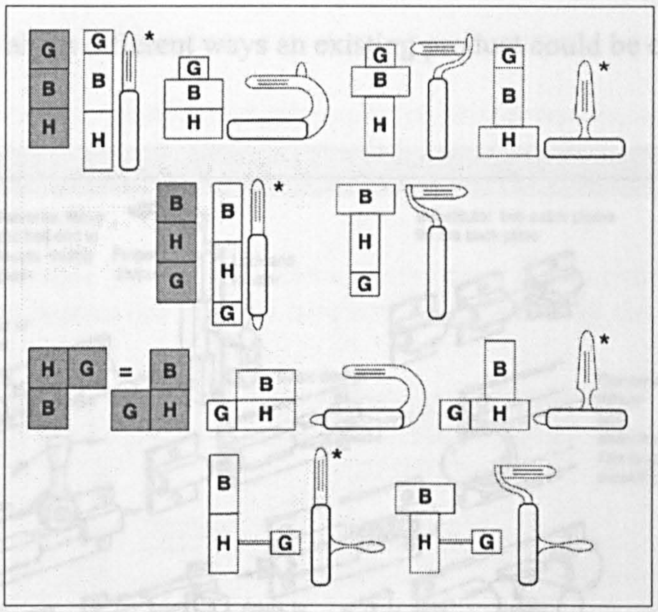

Figure 2.8: The permutation and arrangement of peeler features (Baxter, 1995)

- Orthographic analysis presents two or three attributes of a problem in a graphical two or three-dimensional array (Figure 2.9). This allows possible solutions to be explored by means of combination, permutation, interpolation or extrapolation.

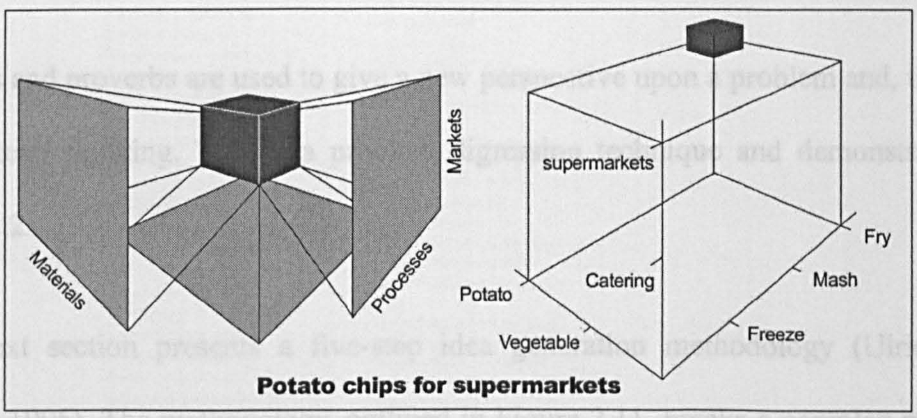

Figure 2.9: The orthographic analysis for problem expansion (Baxter, 1995)

• SCAMPER is an acronym for "substitute, combine, adapt, magnify or minify, eliminate or elaborate and rearrange or reverse" (Figure 2.10). It is intended to stimulate thinking about different ways an existing product could be changed.

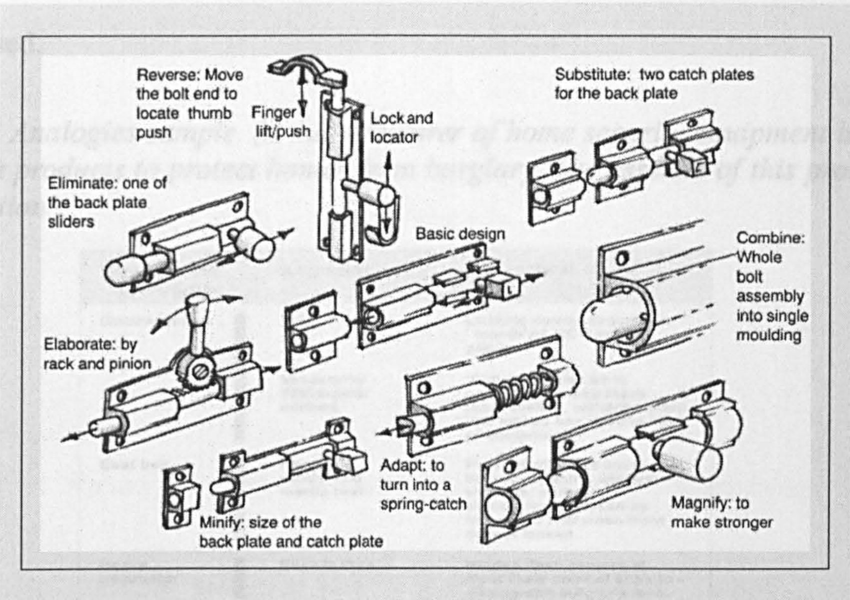

Figure 2.10: A SCAMPER method used for a latch design (Baxter,1995)

• Analogies and metaphors of problems can be used to stimulate lateral thinking. Synectics is a specific technique, involving the use of analogies (Table 2.1).

• Clichés and proverbs are used to give a new perspective upon a problem and, thereby, fuel lateral thinking. This is a problem digression technique and demonstrated in Table 2.2.

The next section presents a five-step idea generation methodology (Ulrich and Eppinger, 1995). The methodology, outlined in Figure 2.11, breaks a complex problem into simpler sub-problems. Solution concepts are then identified for the sub-problems by external and internal search procedures. Classification trees and concept combination tables are then used to explore systematically the space of solution concepts and to integrate the sub-problem solutions into a total solution. Finally, the design team takes a step back to reflect on the validity and applicability of the results, as well as on the process used.

Table 2.1: Analogies sample. (A manufacturer of home security equipment is looking for innovative products to protect homes from burglary. The essence of this problem is seen as 'prevention'.

'Prevention' analogies	Associations	Stimulates ideas
Contraception	Pill	Looking device secured in ' mouth' of VCR or CD player.
	Vasectomy Withdrawal method	'Cut' power cables to equipment; make them inaccessible, withdraw them into locked box fixed to back of equipment.
Seat belt	Head hits windshield Inertia reel	Prevent windows being broken for entry; window shutters; perhaps automatically closed by motorised reel when front door is locked.
Peace negotiator	Face to face	Hidden flash camera at most likely point of entry to photograph burglar's face.
Lifejacket	Flare	Device which switches on all lights and turns stereo on to maximum volume when triggered.

Table 2.2: Using clichés and proverbs to jolt conventional thinking out of a rut (Source: Baxter, 1995)

Most familiar	Most 'visual'
• Practice marks perfect	• When the cat's away the mice will play
• Better late than never	• The early bird catches the worm
• If at first you don't succeed, try, try, try again	• Like father, like son
• Like father, like son	• Kill two birds with one stone
• A place for everything and everything in its place	• Don't count your chickens before they are hatched
• Two wrongs do not make a right	• If the shoe fits wear it
• Two's company, three's a crowd	• Monkey see, monkey do
• Where there's a will there's a way	• A man's home is his castle
• Don't count your chickens before they are hatched	• The bigger they are the harder they fall
• Easier said than done	• Birds of a feather flock together
• All's well that ends well	• Two's company, three's a crowd
• Pracetice what you preach	• You can lead a horse to water but you can't make it drink
• You can't tell a book by its cover	• Don't cry over spilt milk
• An applea day keeps the doctor away	• Two heads are better than one
• A penny saved is a penny earned	• We're all in the same boat
• Cleanliness is next to godliness	• Never bite off more than you can chew
• Mind your own business	• One bad apple spoils the barrel
• Beggars can't be choosers	• Put on your thinking cap
• Easy come easy go	• You can't teach a old dog new tricks
• Beauty is only skin deep	• You can't tell a book by its cover
• Beauty is in the eye of the beholder	• When it rains it pours
• You can't teach an old dog new tricks	• Don't rock the boat
• Better safe than sorry	• Too many cooks spoil the broth
• Two heads are better than one	• Look before you leap
• Actions speak louder than words	• A penny saved is a penny earned

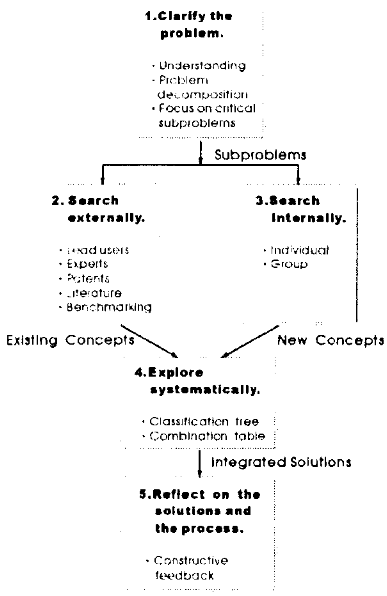

Figure 2.11: The five-step concept generation methodology

Baxter also suggests that ideas should not be judged and evaluated in-depth as they are generated. To develop and evaluate every single idea before generating the next idea would waste an enormous amount of time.

Idea generation is the fruit of creative thinking, whether it is an arbitrary idea or the one inspired by some methodology (Baxter, 1995); i.e., the new idea generated in a systematic way (Ulrich and Eppinger, 1995). However, though these methods are the tool of creative thinking in idea generation; they cannot make explicit the designer's way of thinking. Designers' ways of thinking in terms of cognitive psychology will be compared and contrasted in the following section.

2.2.3 Designer's Thinking and Cognitive Psychology

Most cognitive psychologists agree that the subject matter of cognitive psychology consists of the main internal psychological processes that are involved in making sense of the environment. These processes include attention, perception, learning, memory, language, concept formation, problem solving, and thinking. The term "cognition" was used long ago by philosophers who divided psychology into three components: cognition, conation, and affect (Eysenck, 1993). In this section, the researcher explores the cognitive psychology related to problem solving (designer's thinking).

2.2.3.1 Information-processing theory

Cognitive psychologists agree in a general sense that one of the major goals of cognitive psychology is to provide precise accounts of the internal processes that are involved in the performance of cognitive tasks. Most cognitive psychologists adopt what is often referred to as the information-processing approach (Lachman, Lachman and Butterfield, 1979). Some of the major assumptions of the information-processing approach are as follows:

(1) Information made available by the environment is processed by a series of processing systems (e.g. attention, perception, and short-term memory).

(2) These processing systems transform or alter the information in various systematic ways (e.g. three connected lines are presented to our eyes, but we see a triangle).

(3) The aim of research is to specify the processes and structures (e.g. Long-term

memory) that underlie cognitive performance.

(4) Information processing in people resembles that in computers.

A version of the information-processing approach that was popular approximately 25 years ago is shown in Figure 2.12. According to this version, a stimulus (an environmental event such as a problem or task) is presented to the subject, and this stimulus causes certain internal cognitive processes to occur. These processes ultimately produce the required response or answer. Processing directly affected by the stimulus input is usually described as *stimulus-driven* or *bottom-up processing*. In addition, it is assumed by this version of information-processing theory that only one process occurs at any one moment in time. This is known as *serial processing*, and means that one process is completed before the next begins. The information-processing approach claims that various complex processes occur between the presentation of a stimulus (e.g. an anagram problem) and the subsequent response (e.g. the solution to the anagram). These processes involve transforming the presented information in a number of ways in order to perform the task in question.

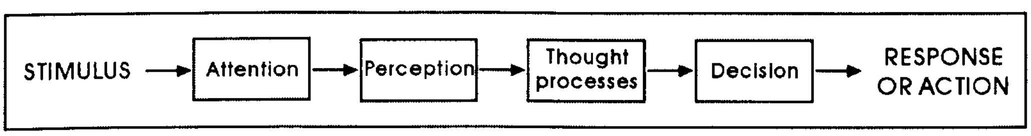

Figure 2.12: The information-processing theory (Source: Eysenck, 1993)

It is widely accepted that most cognition involves a mixture of bottom-up and top-down processing. An especially clear illustration of this comes from a study by Bruner and Postmen (1949) in which people expected to see conventional playing cards presented very briefly. When black hearts were presented, some of the subjects claimed to have seen purple or brown hearts. Here we have an almost literal blending of the black colour stemming from bottom-up processing and of the red colour stemming from top-down processing, due to the expectation that hearts will be red.

A different possibility is that some or all of the processes involved in a cognitive task occur at the same time. This is known as *parallel processing*. In view of the brain's processing power, it seems likely that parallel processing is often used during thinking and problem solving. A third possibility is that tasks are handled by a mixture of serial and parallel processing. In other words, some processes can occur together, but other processes must await the completion of earlier processes. Parallel Processing occurs much more frequently when someone is highly skilled than when they are just beginning to master a skill (Eysenck, 1993).

There has been controversy about the degree of similarity between the functioning of the human brain and that of the computer. There is fairly general agreement, however, that both are information-processing systems. While the human brain often engages in parallel processing, most computers programs function in a serial fashion.

2.2.3.2 Sensory systems and perception

German psychologists in the early twentieth century, who were interested in the figure-ground phenomenon, called the figure in a visual display the "Gestalt", which is a German word meaning "organised whole', and led to them becoming known as the

Gestaltists. They proposed numerous laws of perceptual organisation, but their most basic principle was the *law of Pragnanz*, which is as follows (Kuet Koffka, 1935): "Psychological organisation will always be as 'good' as the prevailing conditions allow. In this definition the term 'good' is undefined" (Eysenck, 1993). Koffka was unnecessarily vague in his second sentence, since a good form was usually regarded by the Gestaltists as being the most simple or uniform of the potential organisational structures.

Many perception theorists have argued persuasively that perception depends on a combination of bottom-up or stimulus-driven processes and top-down or conceptually-driven processes. Gibson(1969) has argued that a stimulus generally contains so much relevant information that bottom-up processes are usually adequate to ensure accurate perception. In contrast, Gregory (1972) claims that perception is an active and constructive process, which makes substantial use of top-down processes. It is probable (as argued by Neisser, 1976) that perception typically involves both bottom-up and top-down processes, with the latter processes becoming more important as the viewing conditions deteriorate.

Marr's (1982) computational theory makes use of information from psychology and neurophysiology to produce computer programs designed to mimic certain aspects of human perception processing. This kind of multi-disciplinary approach to perception will probably be even more important in the future.

2.2.3.3 Attention and memory

The switch of attention and the property of human being's memory are two issues carefully explored in cognitive psychology. There are two main theoretical viewpoints in the area of divided attention research. One is central capacity interference theory. The other proposes that there are actually several different specific-processing mechanisms, all processing limited capacity. A compromise position seems likely, with both a general attention system and more specifics processing mechanisms. This theory would be able to account reasonably well for the effects of task difficulty, task similarity, and practice on performance in studies of divided attention (Eysenck, 1993). An over-reliance on automatic processes can lead to absent-mindedness (Shiffrin, 1977; Shiffrin and Schneider, 1977). Vigilant tasks require attention. There is usually a progressive deterioration of performance over time, known as the vigilance decrement, but it is not yet clear which attention mechanisms produce this (Mackworth, 1950; Broadbent, 1971).

The function of memory is to store information. Storage of information can be looked upon in various ways. Multi-store theorists argued that information proceeds through modality-specific stores and the short-term store before finally reaching the long-term store (Eysenck, 1977). The short-term store is not really homogeneous: we need to distinguish between episodic and semantic long-term memories, and between stores for procedural and for declarative knowledge (Atkinson and Shiffrin, 1968; Tulving, 1972; Parkin, 1982).

2.2.3.4 Thinking (Problem solving)

During the design activity, designers use all sorts of methods (random, methodological, or systematic) for a breakthrough in idea generation. It involves the interaction of human being's attention and memory. In this way, a special pattern of mental work – "thinking" from the viewpoint of cognitive psychologists, is formed. Sometimes, thinking is also considered as the mental manipulation of problem solving. According to Osgood (1953), thinking occurs whenever behaviour is produced for which the relevant cues are not available in the external environment at the time the correct response is required, but must be supplied by the organism itself. From the perspective of cognitive psychology, what we want to know about thinking is what processes are involved. An early attempt to provide this knowledge was the theory put forward by Wallas (1926). He suggested that thinking and problem solving involve a total of four stages:

(1) Preparation, in which relevant information is collected and initial solution attempts are made.

(2) Incubation. In which the individual stops thinking consciously about the problem.

(3) Illumination, in which the way to solve the problem appears suddenly in an insightful way.

(4) Verification, in which the solution is checked for accuracy.

Anderson (1980) claimed that the activity of problem solving typically involves the following three ingredients:

(1) The individual is goal-directed, in the sense of attempting to reach a desired end

state.

(2) Reaching the goal or solution requires a sequence of mental processes rather than simply a single mental process like putting your foot on the brake when you see a red light which is goal-directed behaviour. This single process involved does not usually involve thinking.

(3) The mental processes involved in the task should be cognitive rather than automatic; this ingredient needs to be included to eliminate routine sequences of behaviour, such as dealing a pack of cards.

Design can be looked upon as a behaviour pattern of problem solving because design activity is goal-directed. The sequential mental processes resemble those of the four-stage theory proposed by Wallas (1926).

2.3 CAID Systems

2.3.1 Historic Development of CAID

The computer was originally designed to be a mathematical tool for manipulating abstract symbols, but it was not until the television monitor was added that the results of computations could easily be seen. This visual, rather than written, result gave birth to the electronic image, which was eventually claimed by the artistic community as a new form of artistic expression. Eventually, a graduate student from MIT, Ivan Sutherland, with his doctoral thesis "Sketchpad – A Man Machine Graphical Communication

System', developed and prototyped an interactive computer system that laid the foundations of modern computer graphics. Sutherland's work clearly showed how man and machine could begin to communicate graphically, and demonstrated that the interface between the user and the machine was an important area for development. 'Sketchpad' (later called the 'Robotic draftsman') revealed the potential for non-computer scientists to be able to use a computer for engineering or other professional tasks, predating the whole development of CAD.

The model for computing up until this time was the large mainframe computer often sited centrally in an organisation. To this, users would come with their punched cards, and the machine would process information in batches, with the users returning some time later to collect the results. While this suited the corporate environment, an increasing number of small-and medium-sized companies, as well as many individuals, were denied access to a computer because of their great size and prohibitive price.

The Palo Alto Research Centre (PARC) in California, established by Xerox in 1971, was also aware of this problem, and in 1979 produced the Alto. This machine began the revolutionary upward spiral that resulted in the personal computer. The Alto provided the individual with a personally dedicated computer power with sufficient memory to store application programs, at an affordable cost.

Most classical machines have been designed to perform a single function. Since the Industrial Revolution, in particular, machines have been designed with a single purpose in mind; they have been conceived to fulfil a particular task and, if given other tasks, they usually fail miserably. In the mid-1930s, an English mathematician, Alan Turing, gave considerable thought to the philosophical and mathematical problems underlying this situation. Before then, many kinds of manual and automatic calculators had existed in Europe and the Far East that were able to perform addition, subtraction and multiplication, using data ranging from astrological tables to ocean tide tables. But it was not until Turing's work that the potential of such machines was realised. Turing showed that it was theoretically possible to build a machine that would be able to perform a particular calculation, which transformed one set of numbers into another set of numbers by applying a few simple rules. The machine could then undertake another, entirely different problem by going through the same process of numerical transformation. Turing also saw that rules that dictated the calculations could be built into a machine in the same way as the data that it was processing. So the idea of software (that included both data and application) was given a theoretical underpinning. Because of this universal function, this theoretical machine was known as the Universal Machine, the Turing Machine, or the Universal Turing Machine.

One of the main differences between the computer and all other machines follows from this: a computer has the ability (conceptually) to simulate all other machines. In the world of everyday things these are all very different and separate activities, but since they can be described in some basic procedural sense and translated into software, the computer has the ability to simulate them. The computer can therefore carry out all these activities and many more (depending on its programming), and, in this sense, it is a universal machine.

2.3.1.1 Computers in the realm of Design

The relationship between design and computing did not really have any substance until the development of the Graphical User Interface (GUI). The GUI uses icons, often a palette of small symbols or marks to represent the tools or objects. With the use of icons, it is easier for users to understand how to operate a system that is graphic oriented (Baker, 1993). The introduction of the GUI and other methods of human/computer interaction did a great deal to change designer's perception of computing, since it allowed them, to an extent, to build on their previous experience. After all, designers were not seeking to use computers for their own sake; they just wanted to get on with the job. Early graphical interfaces assumed a model of the user that the designer could recognize. They encouraged a feeling of control over what was done, by allowing the user to display actions and anticipate results. The designers built up a confidence in the computer, which was consistent in action and reaction. The images used for icons were based on real-world objects, such as folders, files and dustbins, which the user could easily recognize and relate to their functions. Human memory was not required to understand the task. Designers were able to apply their visual skills to designing screen layouts, representing information and developing interaction scenarios, while also using their considerable formal repertoire to give shape and feel to the physical product (Baker, 1993).

Computing is now essential to many designers with software packages that allow electronic layout, typesetting, and image manipulation and colour separation. Drafting and drawing software as well as some three-dimensional modelling and rendering programs are quickly moving from 'desirable' to 'required' in such fields as interior design, architecture and industrial design. Animation software allows designers to create moving images for presentation purposes, as well as providing two- and three-dimensional animation for film and television. However, both designers and computer software engineers (who have always had a limited understanding of what constitutes visual image) are not always clear about exactly what kind of design is involved in the application of software packages. The 'designer's way of knowing' – or working – has often been interpreted as a series of stages (see Figure 2.13). The design process starts with a briefing, and progresses through initial sketch ideas to a finished project and evaluation. But this analysis of the various stages involved tends to ignore the classes of design to which the process is applied.

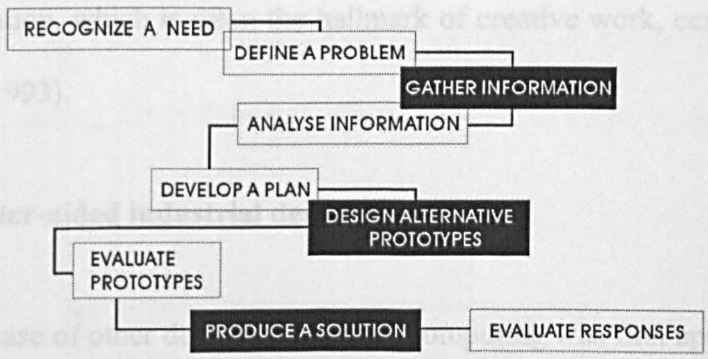

Figure 2.13: The nine-step design process (Whitney, 1993)

2.3.1.2 Computer-aided design (CAD)

Computer-aided design (CAD) was first introduced into the design office to improve productivity. The well-worn arguments that underpinned this move were always concerned with the computer's ability to enhance current techniques, while ensuring that it did not interfere with solidly reliable, traditional work practices. From this it is simple to infer that most of the current software used by designers falls into the routine design. This is because the conceptual framework of the software is dictated by the fact that production advantages can most readily be gained by modifying an existing solution.

The recent development of more 'open systems' of computing allow for an increasingly seamless movement of information from one computer system to another, or from one application to another. Therefore, the ability to combine solutions is now a practical and realistic possibility. This supports the innovation design. It is, however, difficult to find any software that supports the truly creative areas of the initial design activity, particularly when most software systems lack the ability to contain imprecise or 'fuzzy' information, which is often the hallmark of creative work, certainly in its early stages (Baker, 1993).

2.3.1.3 Computer-aided industrial design (CAID)

As in the case of other design disciplines, computing was first applied to industrial design in an attempt to automate existing work practices and skills. Software used in design practices enabled the computerisation of the two-dimensional technical drawing and the three-dimensional modelling – a development that allowed considerable savings in time and money.

In recent years, CAID tools have had a significant impact on industrial designers and their work. Using CAID tools, industrial designers can generate three-dimensional designs on a computer screen and rapidly modify them. In this manner, industrial designers can potentially generate a great number of detailed concepts more quickly, which may lead to more innovative design solutions (Ulrich and Eppinger, 1995).

• Two-dimensional CAID tools

The purpose of 2D graphic software application in industrial design is to visualise the form, texture, and colour of product ideas. Hard copies can be generated with high quality. For this reason, 2D-computer graphic software is taking the place of hand-made renderings. The following examples illustrate how 2D graphic software is applied in industrial design process.

The Mitsubishi Electric Industrial Design Centre (IDC) uses a 2D drawing software, PhotoShop, to create 'digital sketches' in the early design stage (see Figure 2.14 and 2.15). In 1995 IDC began holding an in-house design competition called "CATS" (Computing Art & Technical Shop) in order to improve and share computer skills.

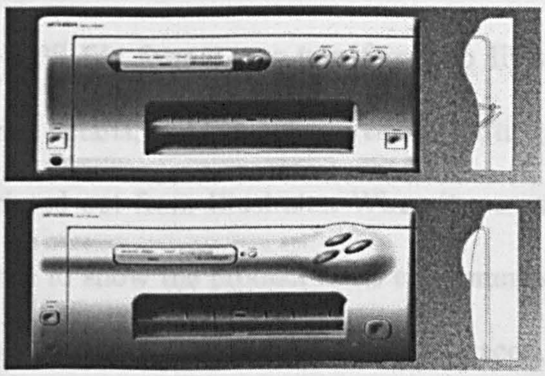

Figure 2.14: the digital sketches of video copy processor created by Mitsubishi

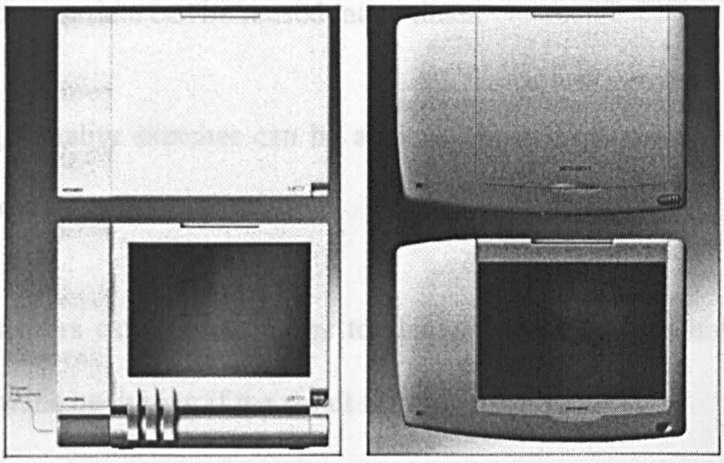

Figure 2.15: The digital sketches of a pen computer created by Mitsubishi

In terms of applications, CATS' designers used "Ashlar Vellum" to create line drawings and "Illustrator" for 2D drawing software. "PhotoShop" or "Illustrator" was used for colouring. Once the Ashlar Vellum CAD system had been used for line drawings, they were usually imported to PhotoShop (with a resolution of 72 dpi) to be coloured. After making the line drawing, the parts to be masked were registered in channels. Colouring was done with the brush tool, with a transparency of 10 to 50%. Next, the data in EPS file format was transferred to Illustrator for drawing in the product graphics and details, and logos, textures and parting lines were added. Finally the sketch was printed out from Illustrator. When it was necessary for designers to use interior sketches to show the product in its environment, the general perspective was checked using Mini-cad. The output was then traced, scanned and finished in PhotoShop.

IDC claimed that digital sketches have some advantages and disadvantages:

Advantages of digital sketches:

(1) The same data can be reused many times.

(2) High quality sketches can be achieved in a short amount of time, improving productivity.

(3) Designers can easily attempt to change design and do not have to start over from the beginning if the result is unsatisfactory.

(4) Computers take up less space than drafters and do not require an exclusive environment.

(5) Digital sketches can draw the attention of third parties more than hand sketches, at least, these days.

(6) Easy colouring and gradations.

(7) Easy to correct. Many variations can be created.

(8) Excellent storing properties.

(9) Small sketches can be enlarged, allowing minute depictions.

(10) High degree of reality.

(11) Sketches do not get dirty or smell.

(12) There is no need to worry about depleting supplies.

Disadvantages of digital sketches:

(1) Initial investment in both hardware and software, and expenses involved in maintaining the latest functionality.

(2) Some people may feel that digital sketching hampers the human qualities necessary for creativity. In order to use computers, sometimes it is necessary to adapt oneself to the machine.

(3) The resolution is determined by the size of the monitor screen. For large objects it is difficult to check the entire object in real size.

(4) The colours of printing differ according to the output hardware (both printers and monitors). Also, the data size must be determined according to the output device.

(5) Data must be managed properly or it is impossible to find past data.

(IDC, 1997)

Because some designers, especially the senior ones, do not accept drawing graphics by using the mouse, it is necessary to integrate traditional hand drawing into the computer graphic system. The following example demonstrates how to use Pro/3DPAINT. Pro/3DPAINT can be used with a stylus and touch pad for hand free drawing, like drawing on a normal paper (Figure 2.16). The user can have a sense of the touch of media. Different effects can be obtained when using different materials. This software also features a rather user-friendly interface. It can meet the designer's requirements by offering pencil, marker, spray, and oil painting. Textures and colours can be mapped directly into the 3D model, which saves the time for ray tracing and lighting (CADesigner, 1997).

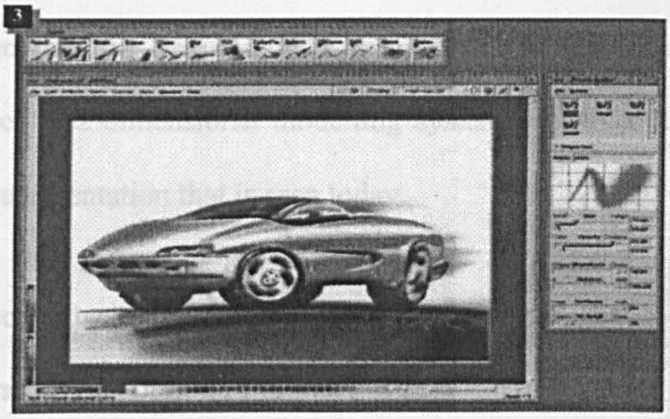

Figure 2.16: A car sketch created by 3D-Paint

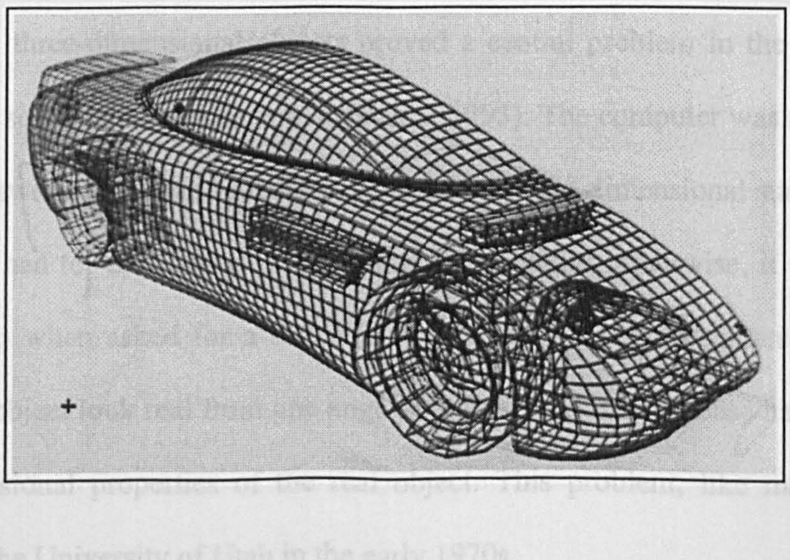

Figure 2.17: A wire-frame image of car (Baker, 1993)

• Three-dimensional CAID tools

Early three-dimensional computer systems displayed simple shapes by tracing the outlines of all the edges, forming an often ambiguous 'wire-frame' image (Figure 2.17). As the objects displayed became more complex, the viewer had great difficulty in understanding the images. Software was therefore written to remove a line if it was hidden behind another line. The convincing representation of solid surfaces was the next breakthrough, so three-dimensional modelling systems began to climb to the level of photo-realistic representation that is seen today.

The perspective techniques that had been used for centuries to provide the illusion of depth were transcribed into the computer system, but there was one drawback. When a painter uses perspective to create an impression of depth, no matter how realistic the impression, if the painting is turned around the object or scene depicted does not appear on the back; the illusion is essentially contained on the surface. The difficulty of describing three-dimensional objects proved a central problem in the development of modelling software for the computer (Baker, 1993). The computer was required to close the gap between reality and illusion displayed on a two-dimensional surface. In order to do this; it had to 'understand' fully in three dimensions, otherwise, it would not know what to do when asked for a different view of the object. Designers only needed to make the object look real from one angle, but the computer database had to simulate all the dimensional properties of the real object. This problem, like many others, was solved at the University of Utah in the early 1970s.

Once the major breakthrough had been achieved, a second issue became clear. This was the realisation that there was a significant difference between the way the three-dimensional images were stored in the database of the computer, and the way in which they were displayed. In the computer, the model was made of edges, their size and relationships. The display of the object was concerned not only with this, but also with the position of the designer, who controlled the perspective of the object, the lighting, texture and scale.

When the real-world situation is translated into computing terms, all these factors have to be calculated to establish the same kind of three-dimensional readings that are normally expected. The difference is that, when using a computer, the calculation has to be driven by conscious choice. The user has to decide exactly what the spatial relationship is between themselves and the object. This is what makes three-dimensional computer modelling often so complex. Not only does the design model have to be built in terms different from its physical counterpart, but information that is normally assumed has to be consciously supplied. In addition, the physical model has other characteristics, such as surface texture and the effect of light. If these are added, as they must be to reinforce the realism of the computer-generated image, then the situation is further complicated.

In spite of its complexity, the three-dimensional computer model is becoming an impressive and powerful new tool. When used effectively, it can provide a new relationship between designers who think in three dimensions (Baker, 1993).

Buckner (1993) stated that three-dimensional models are especially helpful in solving traditionally difficult problems, which are involved in terms of the following aspects:

(1) Assemblies: Parts can be more easily designed to fit together. Some systems have automatic interference checking capabilities and can analyse the effects of tolerance stack-up.

(2) Ergonomics: Software products are available that can place and manipulate human figures to test the human factors of a design.

(3) Aesthetics: Aesthetics can be easily evaluated from any view point by rotating the model on the screen

(4) Manufacturability: The three dimensional details of a part can be defined completely and evaluated for manufacturability long before the part reaches the shop floor.

Despite the vast improvement in modelling systems over the past few years, modelling is still a difficult process. Becoming proficient requires initiative, an open mind, and months of experience. Some of the first tasks for the new user include:

(1) Learning to visualise in 3D: During the modelling process, three-dimensional models are usually displayed on the screen as several orthogonal views and one or more isometric or perspective views. The designer must learn to assimilate all of these 2D views into a three dimensional mental image.

(2) Building a repertoire of commands: There may be several hundred geometry creation and modification commands in a CAID system. Productivity is governed to a large extent by the level of familiarity with these tools.

(3) Developing modelling techniques: Designers generally tend to work with just a few types of form. Automotive designers work with sculptured surfaces; appliance designers may work with more regular shapes like cylinders and planes. It may take some time to develop a modelling technique that is effective for a class of form, but once developed, that technique may be used repeatedly with little variation.

(4) Learning to work around: Every computer system has its quirks. It is part of the learning process to uncover the odd behaviours and find alternate ways to get the desired results.

Three-dimensional modelling is changing some people's minds about what it takes to be a creative designer. Toby Thomson, Professor and Chairman of Industrial, Interior, and Packaging Design at The College of Imaging Arts and Science at Rochester Institute of Technology, comments: "One of the things I've noticed is that we used to think that if you could draw you could think, and if you think, you should be able to draw. Well, that's bunk. We found that there are so many creative people, imaginative people but they don't have those old hand skills that came with the artist type." Roland Johnson, one of the founding fathers of CAID, is currently employed as an industrial design specialist at the Procter & Gamble Company in Cincinnati, Ohio. Johnson believes that 3D modelling may actually help creativity because it can guide one in valid directions and away from invalid directions. He says, "It will save you time because you have to employ your creativity with in more circumscribed boundaries."

Three-dimensional modelling has given designers a medium to describe design ideas more completely than ever before. These computerised 'soft prototypes' can be used to explore and verify design ideas in a fraction of the time required to build physical prototypes, so more of the design and re-design can be accomplished early in the product development cycle when mistakes are less expensive to correct.

However, 3D-computer software still has some shortcomings, which need to overcome. Iwao (1998), a professor of Tsukuba College of Technology, Japan, stated his view of three-dimensional modelling, "3D-CG is basically available on the utilisation of computers in early conceptual design phase, but it is not actually utilised, because of the reasons as follows."

(1) In the early stage of the conceptual design phase, there is a lack of image data, and there is a necessity for studies of many ideas, CAID systems lack the necessary flexibility.

(2) There is no software, which can build 3-dimensional images quickly and easily, and the available software is expensive.

(3) There is little time to master the software, due to other workloads.

(4) There is a financial burden to purchasing the software.

(5) The time required to master the software is converted into a cost, which cannot be ignored.

Van Dijk (1995) also explained why people do not use 3D CAD during conceptual design. He claims the available systems are simply not adequate, that is, the designer obtains no useful results by using the system and there are currently no CAD systems that live up to requirements of conceptual design. The requirements for CAD systems themselves to support conceptual design are not clear, and are biased by the deficiencies of the existing but unsuitable systems. Researchers have described the deficiencies of traditional CAD systems when applied to the conceptual phase of industrial design (Athavankar, 1990; Pentland, 1987; Tovey, 1989). In van Dijk's articles, he recommended some of the initial requirements for CAD in the conceptual design phases.

(1) Easy data entry: Entry of geometric data must be quick and easy, both to specify and to modify. According to Tovey, numeric data and typed data present difficulties, e.g. to stylists.

(2) Hand movements: To complement the thinking process, designers should not separate the feel of geometry and hand movements from the process of shape generation and manipulation. Designers need to maintain a direct relation between hand movements and modelling operations.

(3) Imprecise data: Because early conceptual sketches are meant primarily for the designer's own feedback, shorthand notations are used. When figuring out the details, the designer fills in the implied information. It would prohibit an unhindered flow of thoughts if the designer had to think about exact size and dimensions at the early conceptual design stage. Consequently, the system's object representation must be capable of handling imprecise data. (This is more or less a contradiction of the precise data needed to represent an object's shape in the computer, and to perceive this shape on a computer screen.)

(4) Switch to details: Top-down development from non-detailed sketch model to a well-defined and detailed concept is, in general, not the way designers work. CAD systems have to allow the designer to zoom in on specific features, while temporarily forgetting about others. We must be able to handle such features tentatively so that the commitment to such a feature is not insisted upon. The system will have to support switching between different levels of detail.

(5) Review alternatives: It must be possible to view design alternatives for comparison.

(6) Separate conceptual design system: Several object representations are needed to support the full design cycle: one for each of the different stages of design. Initial sketching of a 3D model demands a representation as described above. Later design stages demand the ability for detailed, precise control. This calls for separate CAD systems, each with their own particular object representation and user interface.

(7) Clay modelling: Current CGS-based solid modelling techniques are unlikely to be accepted for free-form shape generation. Alternatively, a system that mimics hand sketching is inherently a 2D tool. Imitating clay modelling is more promising. In such a system, a shape can be interactively reformed and evaluated.

2.3.2 The New CAID Systems and their Development

Though the commercialised 3D CAID systems have been widely used, the researchers mentioned above have pinpointed some drawbacks to be improved. Van

Elas and Vergeest (1997) have also claimed that conceptual design, using conventional 3D CAD systems, is a controversial issue among industrial designers. Although one can produce complex, accurate, finished 3D models using these CAD systems, it is still difficult to use them during early, creative product design. They created a new function called the Displacement Feature Function (DFF) which allows the designers to design a displacement feature in a specific way. First the region that is to be displaced has to be defined on the given surface model. The designer can sketch data points directly onto the surface.

In DFF, a feature boundary curve is fitted through these data points automatically, ensuring that the resulting curve lies exactly on the surface. A closed feature boundary can consist of one or more freehand sketched curves that are connected automatically to form a non-self-intersection loop. Once the designer has sketched the feature boundary, the corresponding displacement feature can be calculated and displayed immediately. As soon as the displacement feature is displayed, a window appears with several sliders (Figure 2.18). Each of these sliders controls one parameter of the displacement feature. There are sliders for the rounding parameters, amount of displacement, and there is one slider that allows scaling of the feature boundary that encloses the displaced region. Furthermore, the designer can, optionally, show the sketched feature boundary and the feature boundary that encloses the displaced region.

Using this window, the designer can alter any parameter of the displacement feature by simply dragging the corresponding slider to a different value. The DFF provides visual feedback cues, and the displacement feature is updated immediately. In this way, the designer has full control over the shape of the feature.

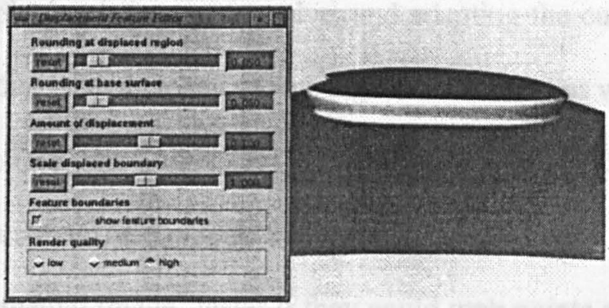

Figure 2.18: The interface to control the shape of the feature in DFF

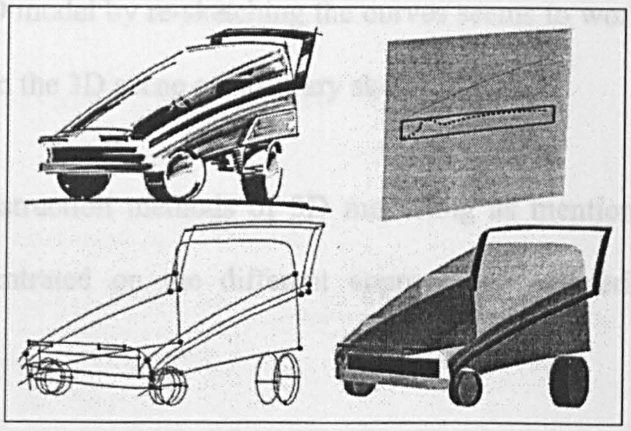

Figure 2.19: The car concept by Gianni Orsini, with sketched curve, curve mesh, and FSD model

Another issue focuses upon how to improve the construction of 3D models and integrate manual drawing habits. Van Dijk (1995) created a new piece of software, the Fast Shape Design, a prototype CAD system that tries to realize the requirements of the conceptual phase of industrial design. Figure 2.19 illustrates the similarity between a traditionally sketched design concept and the corresponding FSD model. The curves that make up the curve mesh are sketched in the same perspective as in the traditional approach. The whole system thrives on direct manipulation, from the sketch input to the pick –and –drag manipulator. The FSD's object oriented data structure and its graphical user interface have been described (van Dijk, 1992), as have the different types of transfinite surface patches that interpolate the curve mesh (van Dijk, 1993). The system is completely interactive; a designer can change a model by picking one of the curves, placing it in a perspective, and adapting the curve by sketching. The part of the curve that is re-sketched will change immediately, as will the surface patches bordering on this curve. Van Dijk stated that the sketch input might not be the perfect tool for building up a 3D surface model. Some designers (subjects) suggested that they would achieve their 'mental image' faster if they could grab points and tangents on a curve. Best results are obtained if the initial curve is sketched in an orthogonal view using the tablet and stylus. However, changing a 3D model by re-sketching the curves seems to work very well, as does sketching directly in the 3D scene on arbitrary sketch planes.

Except for the construction methods of 3D modelling as mentioned above, the other researchers concentrated on the different approaches considering systematic construction.

Chang (1995) presented a new system, Basic Elements Generating Form system, which is specifically for the furniture styling of Chinese Ming-Dynasty chairs. The system is based on a CAID system model (Figure 2.20) with a form elements database (cell library) which is constructed by Microstation, a 3D modelling software, and saved under dBase. He utilised the functions of Microstation to compose a Microstation-centre design system (Figure 2.21). With utilising Microstation functions, each part belonging to the chair and its inter-relationships with Microstation are described specifically in Figure 2.21. The C++ environment and dBase database communicate with the inner system of Microstation through the Microstation's MDL interface. The key points of Chang's study concentrated on the way designers extract the parts of the cell library to generate alternative models through the filtering of the evaluation units; and to construct a model or compose a set of parts into a chair using the parameters of Microstation from the cell library. One of the chair models is shown in Figure 2.22.

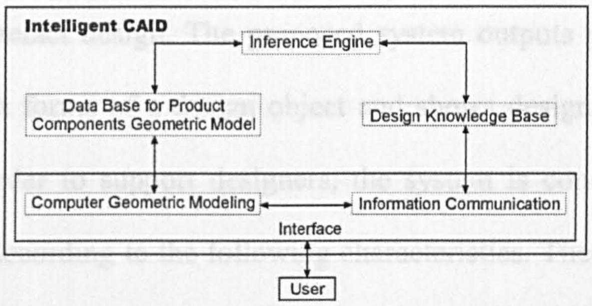

Figure 2.20: The model of the intelligent CAID system

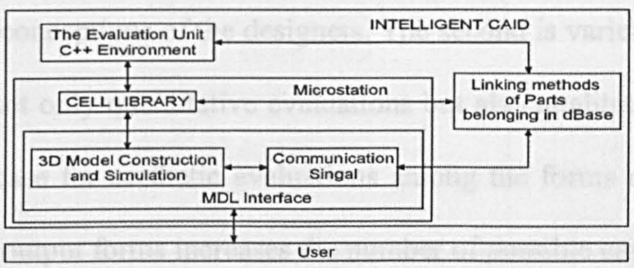

Figure 2.21: The Microstation –centred model of the intelligent CAID system

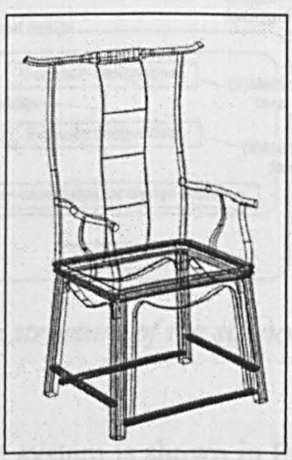

Figure 2.22: One of the chair models of the Ming –dynasty style

Yujin (1998) also demonstrated another new system, the Element Generation Method, which helps the designer take into consideration the basic form in the early stage of artefact design. The proposed system outputs potential candidates for design solutions as forms of a design object and shows designers the solutions in a concrete form. In order to support designers, the system is constructed so that the forms are generated according to the following characteristics. The first is novelty of form. When designers examine candidates for design solutions, preconceptions may serve to narrow the search space needlessly, thus preventing the output of novel forms. The proposed system allows ideas to be obtained without the unnecessary elimination of novel forms due to preconceptions of the designers. The second is variety of forms. In the evaluation of form, not only quantitative evaluations but also qualitative ones must be performed, as is the case for aesthetic evaluations among the forms output from the system. The variety of output forms increases the number of possible candidates for design solutions.

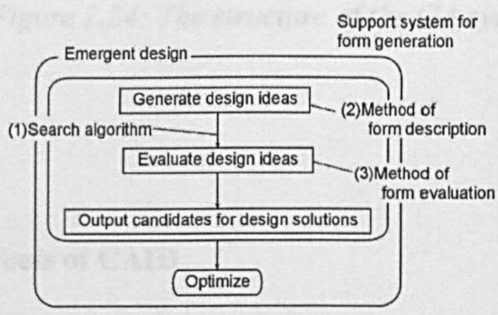

Figure 2.23: The basic structure of the support system for form generation

The basic structure of the system is shown in Figure 2.23. Constructing the system according to the above mentioned principles requires determination of the following: (1) search algorithm not based on reductionism to output design solutions, (2) method of form description that provides various forms with few restrictions, (3) method of form evaluation. All candidates for design solutions are evaluated and the fitness is calculated in GA (Genetic Algorithm is one such search algorithm. It is an optimising algorithm that outputs possible solutions by evolving the chromosome, which is a set of variables that describes the design object). According to the fitness, GA operations such as selection, crossing and mutation are executed to the chromosomes. Therefore, determining the fitness is necessary in the application of GA (Figure 2.24).

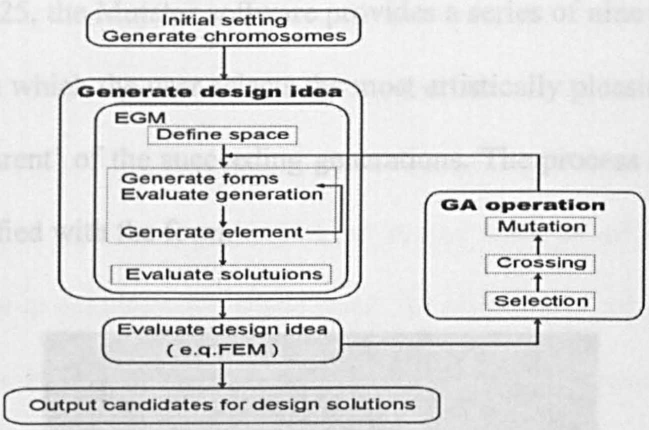

Figure 2.24: The structure of the GA system

2.3.3 The Possible Tools of CAID

Another area of software development that holds potential for art and design is the computer algorithm based on an evolutionary process – or genetic algorithm, as they are newly called. This approach was developed in the 1970s, when the workings of biological evolution were used as a model for software design. Such software solves quite simple biological problems emulating evolutionary processes, so that the solutions become increasingly apposite, the longer the software is allowed to run. The aim of the algorithm is to produce a 'better' solution each time, and in this sense it mimics the biological process very closely.

Todd, Latham and Hughes (1991) used another piece of software, Mutator, which provides a subjective user interface for the final stage of form design. The system is based on the natural process of mutation and breeding by marriage, but with the artist-controlled aesthetic selection deciding which forms survive and breed, and which forms die. In Figure 2.25, the Mutator software provides a series of nine images that resemble each other, from which the user selects the most artistically pleasing. If one survives, it becomes the 'parent' of the succeeding generations. The process can be repeated until the artist is satisfied with the form.

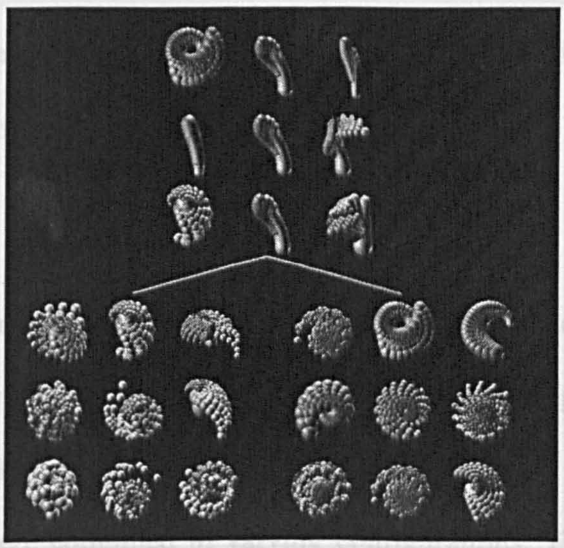

Figure 2.25: A series of nine images created by the Mutator

In the field of biochemistry, for example, the 'Meta Dendral' software has been used to generate new rules for analysing molecules. Another example is given by Suran

Goonatilake: 'the artificial intelligence group of the Lockheed Aeronautical System has used genetic algorithm in the parametric design of aircraft. The task involves finding compatible configurations of wing sizes, fuselages, tail lengths and engines for a given class of aircraft. It is an extremely difficult problem, where as many as thirty parameters may be under consideration (Goonatilake, 1991).

Another computer technique has been drawn from computational linguistics and applied to the understanding and development of visual form. It is termed 'shape grammar' – a name that represents its roots in both images and language. Our everyday language can be broken down into various rules that underlie and organise its use. Computer systems are also based on rules, and complex problems can be handled when a series of rules is used, as is evident from recent work in artificial intelligence. Of particular interest to designers are shape rules. A collection of related shape rules forms a shape grammar, and as a natural extension of this idea, any designs that are the result of applying both shape rules and shape grammar constitute a shape language. (Baker, 1993)

Shape grammar has also been used in architecture to create a series of plans from a simple formula. A range of plan forms was constructed at Hong Kong Polytechnic with direction from William Fawcett (Figure 2.26). They were made up of individual components that were combined in varying configurations. The process is rather like selecting items from a catalogue of parts. The major difference is that in the shape grammar, the rules for selection have to be explicitly stated, whereas an architect could make a visual selection of components from a catalogue – windows, doors etc. – using implicit criteria that would never need to be formally stated.

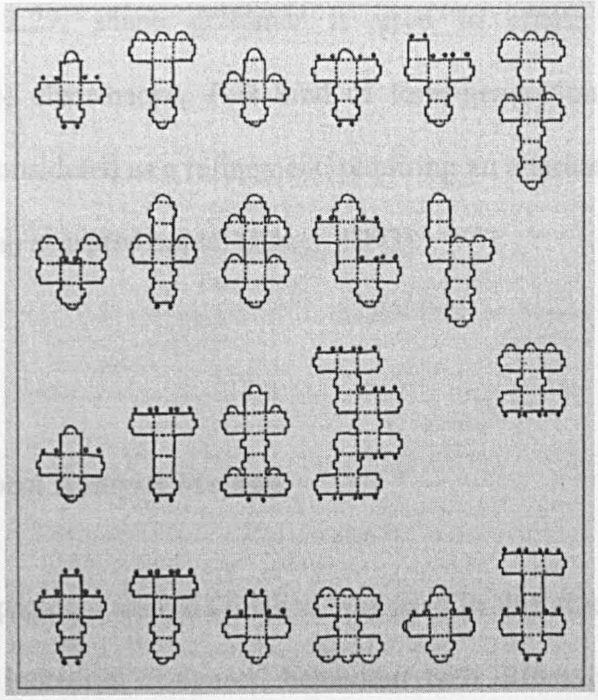

Figure 2.26: A series of plans from a simple formula of shape grammar

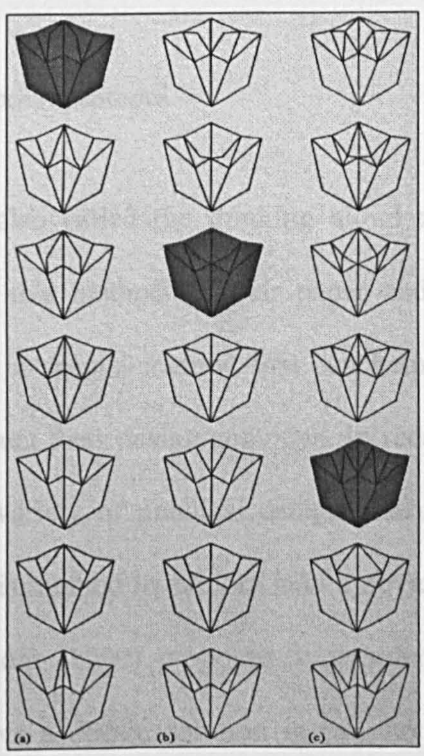

Figure 2.27: The alternative shapes of Hepplewhite-style chair-backs

In Figure 2.27, shape grammar is used to create alternative shapes for Hepplewhite-style chair-backs. This kind of form-generation technique is best used when design is considered as a refinement, requiring an alternative set of solutions to be developed from an accepted model (Baker, 1993).

2.4 Verbal Protocol Analysis Method

The verbal protocol analysis method was used in this study in order to extract the discrepancies of industrial designers' behaviour with different CAID systems used to conduct designs. This method is explained below.

2.4.1 Studies related to verbal protocol

Verbal Protocol is also called the thinking aloud method. Ericsson and Simon (1993) first investigated this method in their paper and Van Sowere et. al., (1994) further developed it into a special method that can help researchers understand how designers think and conduct their design activities. In recent years, verbal protocol has been applied to a wide variety of practical design researches. For example, Lee and Radclliffe (1990) used this method to explore how a novice designer finds the solution. In his experiment, Guindin (1990) proposed a complicated problem and asked the software engineer to solve a design solution in two hours. The subjects' behaviours were recorded and subsequently analysed.

Visser (1989) observed the process mechanical designers used to perform their design. During the experimental period of 3 weeks, emphasis was placed upon problem solving. Furthermore, Visser (1992) explored in detail the design process software engineers used to approach multi-disciplinary design problems. Davies (1991) also studied the practical design process of software engineers and came to the conclusion that the design activity involves different layers of cognitive process. More importantly, Lloyed and Scott (1994) synthesised an outer framework of design activity by using the protocol method. Stauffer (1987) and Stauffer and Ullman (1991) used open-ended questions to explore mechanical designers' thinking processes. In a period of time up to 10 hours, their behaviours and design process were recorded for further analysis. In addition, Suma and Tversky (1997) used protocol methods to investigate the differences between architects and design students in terms of the sketches they used to solve design problems and the information categories involved.

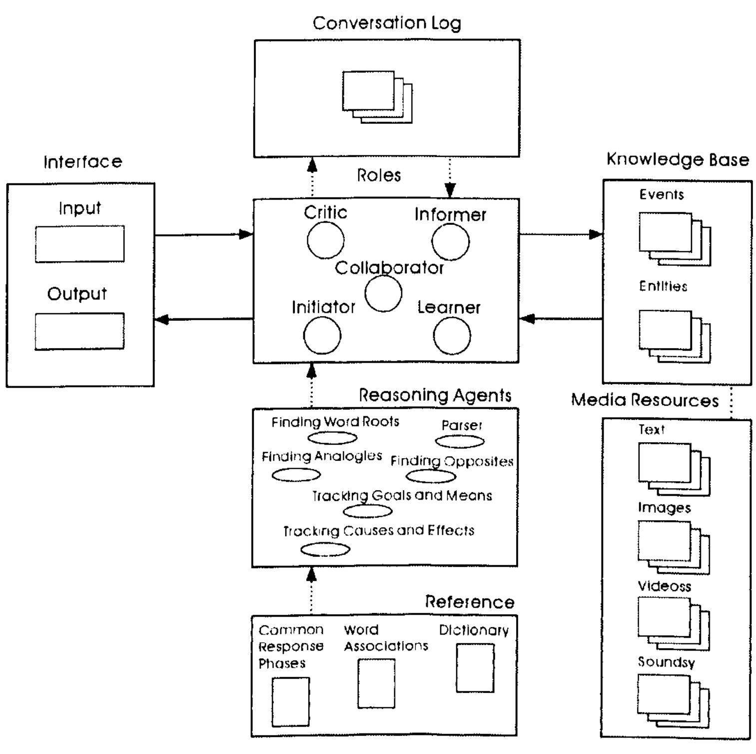

Figure 2.28: The proposed design conversation system

Lawson and Loke (1997) discussed the problem of CAD in architectural design from the point of view of adding creativity. They concluded that, at least until design conversations are better understood we should concentrate less on pictures and more on words. They also attempted to develop a computer-aided design conversation system. Figure 2.28 is the structure of their proposed design conversation system. Such a system would be word-based, and would take advantage of the evocativeness as well as the flexibility of works in describing and negotiating meanings. Input and output of the system are in the form of structured sentences with prescribed syntactical rules. It is not the intention of the system to emulate natural language conversation, but rather to retrieve relevant or potentially relevant concepts and ideas that may feed the creative design process. Lawson and Loke's study shows that the protocol method is a better way to record and analyse designer's design activities both of individual and team members.

Atman et al., (1999) also compared the freshman and senior engineers in design process by a protocol method. In this study, they analysed the protocol to document and compared the student's design processes. Their results showed that the seniors produced higher quality design. In addition, compared to the freshman, the seniors gathered more information, considered more alternative solutions, transitioned more frequently between design steps and progressed further into the final steps of the design process.

2.4.2 The verbal protocol analysis method

Verbal protocol analysis has been mentioned briefly in Chapter 1. In this section, the researcher will discuss the steps and contents of this method in detail.

As mentioned above, the verbal protocol analysis method has been applied to different design fields. However, only Gero and Mc Neill (1998) have discussed and compared this method with other research methods. Several key issues about their discussions regarding the verbal protocol method are covered in the following sections.

2.4.2.1 Design reasoning

In most cases, the verbal protocol data of the subject is huge, but it is random, unprocessed raw data. To understand the detailed design behaviour and thinking, a framework of such data is needed. Such kinds of framework are up to the interactive behaviour design they have in their problem domain and the models of design reasoning.

Based upon the framework of the verbal protocol method, the idea development process can be considered as a specific series of strategies designers adopt to solve problems through they're interpretation of the design problem. To easily analyse the design process, one needs to classify and record the strategies designers adopt in the problem domain. The process of this method can be seen in Figure 2.29.

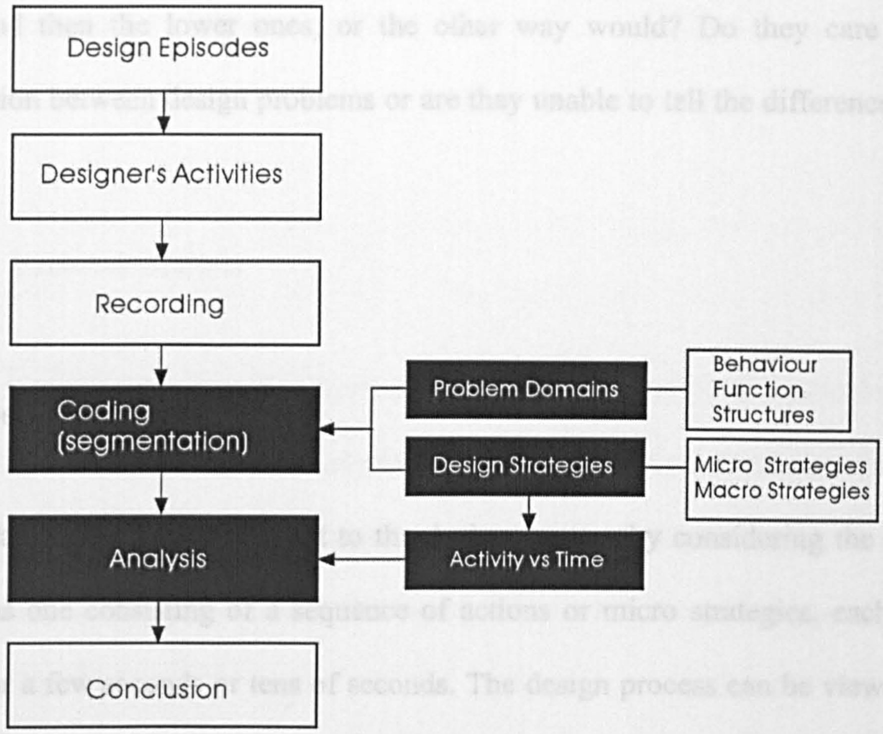

Figure 2.29: The flow chart of verbal protocol analysis

2.4.2.2 Problem domain

The problem domain refers to the classification and layers of the design problem that the designers encounter. Gero and Mc Neill (1998) claim that the classification of the problem domain involves function, behaviour and structure. Here the function relates to the purpose of an artefact and behaviour relates to the actions or processes of an object or artefact. Reasoning in structure involves the manipulation of object or its relations to bring about a physical solution. They claimed that these three items vary in different design fields and problems.

The problem domain's layer is defined by the degree the designers care about some of the issues in manipulating their design problem. Do they think first about the higher layers and then the lower ones, or the other way would? Do they care about the interrelation between design problems or are they unable to tell the differences between them?

2.4.2.3 Design strategies

A framework can be brought to the design process by considering the designer's activity as one consisting of a sequence of actions or micro strategies, each typically lasting for a few seconds or tens of seconds. The design process can be viewed as one, which the designer engages the design problem by using a repertoire of micro strategies (The micro strategies was addressed in Chapter 5).

Classifying the micro strategies into a small number of groups can enrich the representation. The results are a view that is both data driven, in that the protocols are the source of the repertoire, and model driven since models of design are used to add further structure to the repertoire. The number of different micro strategies that can be identified in a design process is dependent on both the designer's experience and on the complexity of the problem.

In addition to identifying micro strategies, the designer's approach can be viewed in the longer term with the designer executing a long-term plan or macro strategy typically lasting several minutes. Macro strategies can be identified by looking beyond the current state and by assessing the designer's behaviour in the context of the whole design solution. The macro strategy dimension adds richness to the representation by adding context to the micro strategies.

2.4.2.4 Protocol analysis

The approach to protocol analysis described in this study involves the development of a coding scheme during the analysis. The protocol is segmented; a coding scheme developed and the segments categorised. Before presenting the coding method used, the design episodes are discussed, and the coding scheme and the processing of the results would be described.

The experimenter and each designer from a normal design practice selected the design tasks. The sessions were recorded in the designer's normal place of work. The designers verbalised their thoughts during the design episodes. The designers were video taped. The video equipment was configured to look over the shoulder of the designers and to impact as little as possible on the designers. Each designer's speech was transcribed and time coded. A description of the designer's actions was added to the record.

2.4.2.5 Design episodes

Design episodes vary in different research areas and are often up to the experimenter. The experimenter, therefore, needs to understand the differences in the design episode's difficulty and the period of time they may take. Moreover, different contents might be assigned on account of the experimental purpose. The subject's experience is the final thing that needs to be taken into consideration.

If the experimenter thinks that the realm of the design episodes (really exist or should be taken care of) will affect the experiment, then he or she should carefully decide to observe the realistic design problem or the laboratory-controlled problem.

2.4.2.6 Segmentation

Van Someren et al., (1994) described a process of aggregation of segments into "episodes." The method focused on designer's actions or intentions. The protocol is divided along lines of designer's intentions. The designer's intention is interpreted for each segment. (A segment in terminology corresponds closely to an episode in the terminology of van Someren et al.) A change in intention flags the start of a new segment. The segment coding includes the time; designer's words (dialogue), designer's actions and the categories of micro strategies. The coding should be done by the protocol sequence according to the designer's intentions. Actions mean the designers are doing something, for example, sketching, reading, typing, or clicking any object.

2.4.2.7 Coding scheme

The coding scheme is allowed to evolve during the analysis. As segments are identified which do not fall neatly into the existing scheme, then a new category will be introduced or an existing category will be redefined. A detailed coding scheme is explained in the section 5.2.4.

2.4.2.8 Coding consistency

By comparing the results achieved at each stage in the coding process, it is possible to assess the robustness of the approach and to identify areas within the approach that may be improved. It can also be used to give an indication of the validity of the results. The consistency of the coding method is assessed by comparing each of the protocols with each other to establish the level of agreement between protocols.

2.4.2.9 Activity Vs time

For each of the protocols the results of the coding are recorded on a single graph. Each of the coding dimensions is plotted against time. This includes the time axis that represents the segment lengths in the context of the overall design episode. The categories of micro strategy dimension are often omitted so that the graphs can be easily understood.

2.4.3 Summary

Thinking aloud or protocol technique is a means of capturing and representing design carried out by human designers as a sequence of activities. The think aloud or protocol technique is extended through the use of a domain-dependent coding scheme based on generic models of designing and a more robust coding methodology. This produces a much richer coding structure. As a consequence, more information becomes available.

The analysis methods developed and applied from research provide the basis for articulating different aspects of the behaviour of individual designers, and for distinguishing the behaviours of different designers.

The development of such a tool as the one described in the last section offers opportunities for "measuring" designing. It now becomes possible to test different hypotheses about how designers manipulate their designing tasks. The application of this approach to the analysis of design protocols should provide a basis for a better understanding of designing, as well as the basis for possible future computer-based design aids. That is one of the reasons why the researcher chose this method as a tool to explore designer's behaviours in a CAID environment.

2.5 Summary

CAID systems have been widely employed in industrial design. There exist, however, some problems in the application of the practical design activities. CAID systems benefit designers and manufacturers in many aspects and this is supported by the research in this chapter. However, the CAID systems themselves can be grouped into the following categories:

(1) 2D graphic software: This kind of graphic software supports drawings and idea sketches. It can be operated by mouse and keyboard for data entry. In some software such as the Digital pad and Stylus, traditional free hand sketching is also doing well.

(2) 3D modelling software: This sort of CAID system is more suitable for the idea refinement and engineering-oriented model construction in the later phase of industrial design procedure. 3D modelling software not only offers a nearly photo realistic visual presentation but also clearly shows the detail of the design proposals. It is considered as an indispensable tool in the verification of ideas and the core stage for development of the engineering design from the industrial design.

(3) Algorithm-driven software: This kind of software uses a database, e.g., cell library, to generate ideas, attempting to provide designers with more options. From the literature review, it is clear that this kind of software can be applied to practical design cases. The relationships between the properties of the algorithm-driven software (Ulrich and Eppinger, 1995) and the phases of industrial design procedure can be illustrated in Figure 2.30.

It can be seen from Figure 2.30 that 2D and algorithm-driven software are used more in conceptualisation and the preliminary refinement stages. Algorithm-driven software can also support designers in finding concepts. On the contrary, 3D CAID software is often applied to the later stages of design process: further refinement, control drawing, and co-ordination with engineering. This indicates that, if designers want to perform the design activity smoothly, they need to master all three kinds of CAID systems. Because the algorithm software is still under development and not fully applied to practical design, it is not clear how it will affect the design activity. In other words, the most frequently used CAID software today is 2D and 3D software.

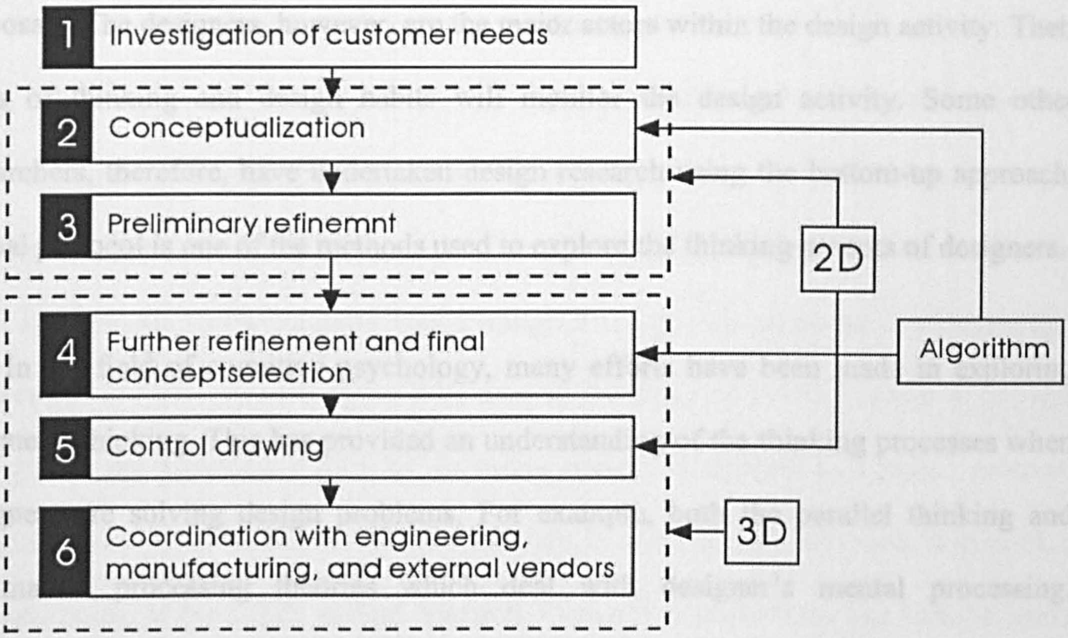

Figure 2.30: The properties of CAD tools and phases of industrial design

The analysis of 3D CAID systems research also shows that people are attempting to apply the operating method of 2D software to 3D graphic software, where free hand drawing is simulated. That is to say, the traditional manual way of drawing is being applied to develop the ideal way of 3D modelling. Research also shows that it still takes time to achieve this goal.

In terms of algorithm-driven software, researchers are attempting to support the designers' creativity in a more automatic way. This will meet the requirements of some specific cases; for example, the emergent design condition in a GA system mentioned by Yujin (1998).

Both 3D and algorithm-driven software research are based upon the top-down process in which the design activity is considered as a holistic process of specific patterns. Characteristics of these systems and their use were observed to move their proposals. The designers, however, are the major actors within the design activity. Their ways of thinking and design habits will monitor the design activity. Some other researchers, therefore, have undertaken design research using the bottom-up approach. Verbal protocol is one of the methods used to explore the thinking process of designers.

In the field of cognitive psychology, many efforts have been made in exploring designers' thinking. This has provided an understanding of the thinking processes when designers are solving design problems. For example, both the parallel thinking and information processing theories which deal with designer's mental processing. Furthermore, psychologists also claim that people perceive the things around them through their senses. Such kind of thinking often mixes the bottom-up and top-down approaches (Bruner and Postman, 1949). Results of the above research were systematically analysed and segmented into the strategy items mentioned in Section 2.4 and could serve as the basis for verbal protocol analysis. In the past, verbal protocols were mainly used to compare the different thinking processes between senior and junior designers or between design students and professional designers (Gero and Maher, 1993; Ericsson and Simon, 1993; Suwa and Tversky, 1997; Atman, 1999). Though their research domains are not industrial design, the essence of their research is closely related to the design activity of industrial design. Gero and Mc Neill (1997) also pointed out that verbal protocol analysis is suitable for different design issues. For instance, what is the difference between student designers before and after they take a design course, and are there differences when designing with and without computer aids? This methodology can provide a basis for a better understanding of designing as well as the basis for possible future computer-based design aids.

This study, will therefore, focus upon how designers conduct their design activities using CAID systems. Do they encounter different problems? Are some operating methods more suitable for product design? Is the designer's way of thinking the major issue to be considered for the systematic research of CAID systems, which need to be more sympathetic to the human-centred design activity? Verbal protocol analysis and observation (by video recording) will be used in the study of CAID in order to explore and answer the problems. From the literature review, it appears that verbal protocol analysis has not been used in CAID study before. It is hoped that this study will mark a new beginning of the CAID system research. Concrete contributions can then be made for other researchers that are interested in this domain.

Chapter 3 A Survey of Computer-Aided Industrial Design

3.1 Introduction

In the early phase of the development of computer graphic techniques, the purpose was simply to display the data on the screen and to print the hard copy through a printer. Later developments made it possible for designers to construct models and images of objects. Moreover, the design data could be simulated, analysed, and stored in the memory. Such techniques have also been applied to engineering, architecture, physics, chemistry, mathematics, and medicine. Even the simulation of the atmosphere in nature is possible with computer graphic techniques.

In the past ten years, CAD system engineers have made big strides in the application of computer-aided design (CAD) techniques to 3-dimensional product form simulation. Particularly, the CAD techniques that originally required powerful workstations have now been adapted to the personal computer due to this remarkable progress of speed and memory. This indicates that designers can, with a reasonable budget, invest money in the CAD software that was originally available only on expensive dedicated workstations such as IDEAS, Alias, and Pro-Engineer. Once the price drops to an acceptable level for general design houses, designers will apply these CAD techniques to their design activities. In this way, the computer can help a designer, who is familiar with the tool, to visualise his or her ideas through simple mouse clicking. Moreover, the drawing on the screen can have a photo realistic quality; i.e., it looks just like an image of a real product. The kinaesthetic touches seen in hand-made drawings no longer exist. It is, therefore, possible for designers to predict the real context of the final product through computer simulation. In terms of reliability, the computation technique can clearly define the location, shape, and dimension of the product through complicated geometric calculation. Once the 3-dimensional model is finished, the designer can easily produce the engineering drawings with precise dimensions. This data can be further transmitted to a CAM system so as to generate the solid model either by a CNC lathe or a laser rapid prototyping machine. The properties of high efficiency, quality, and reliability are what designers are looking for. The construction and simulation tools of 3D-computer software, therefore, are some of the best design tools for designers in the modern era where efficiency is always a high priority. In this chapter, the researcher has made a survey of product designers in the application of CAID systems. The present status of use and associated problems were explored.

3.2 The Current Status of CAID Application

Taiwan started to apply CAID from the early 1980s. Among the CAID systems, Auto-CAD was a very popular 2D-computer drawing software package in Taiwan during those years because the price was reasonable, and the user interface was not too complicated. For engineering drawings, no other drawing software could beat Auto-CAD. For other design professions, software like Illustrator and Freehand that were available only in Macintosh computers, were also used. When the PC versions of these drawing software were developed, there was a rapid growth in using such software in practical design activities because most of the personal computers in Taiwan were IBM compatible. Consequently, designers in Taiwan were supported in a much more economical and faster way in computer technology development than those designers in other countries. The change of the PC version into the MS-DOS system for the graphic software was good news to Taiwanese designers because they had been developed well in the Macintosh computers. Designers from the field of graphic design, electronic media, and product design and development all adapted to CAD techniques. More importantly, the launch of Windows 95 in 1994, whose interface design was as user friendly as the Macintosh, greatly boosted this trend. Designers could replace the command driven MS-DOS environment with a WIMP environment, and with this change the worry about the system's complexity was gone, and this drew many more designers to use computers for their creative jobs. The revolution of the windows operation system encouraged even the experienced designers to substitute computers for their traditional design and drawing tools. Though computers could save time for the regeneration and manage the database more efficiently, the 2D visual image of the product did not accurately represent the design ideas. This problem was not resolved until the wide spread introduction of 3D CAD software. Different from its 2D counterparts, the 3D software allowed the representation of the design ideas more precisely; thus designers could produce a more realistic version of their design solution to help the tasks of idea evaluation and refining.

It is common for product designers to use 2D and 3D CAD software in the design development phase. This indicates that CAD systems have been deeply involved in design activities and affected the quality of design. This study, is therefore, aimed at understanding how 2D and 3D CAD software are used in design development, how they influence the design process, and what are the characteristics of these software packages.

The different CAID software packages used at the present

There is a wide variety of CAD software, each of which has special functions and features. Generally speaking, CAD software can be categorised into the following groups:

(1) 2D drawing software: for example CorelDraw, Freehand, Illustrator, and PhotoShop, and so on. This kind of software is used mainly in drawing, illustration, and advertising. For example, PhotoShop is used mainly for image processing, but is also used for special visual effects. Figure 3.1 shows an image generated in CorelDraw and processed in PhotoShop.

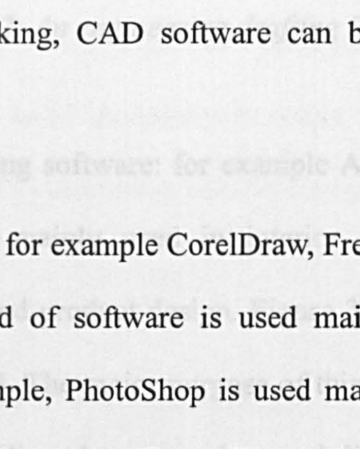

Figure 3.1: A Hello Kitty generated in CorelDraw and PhotoShop

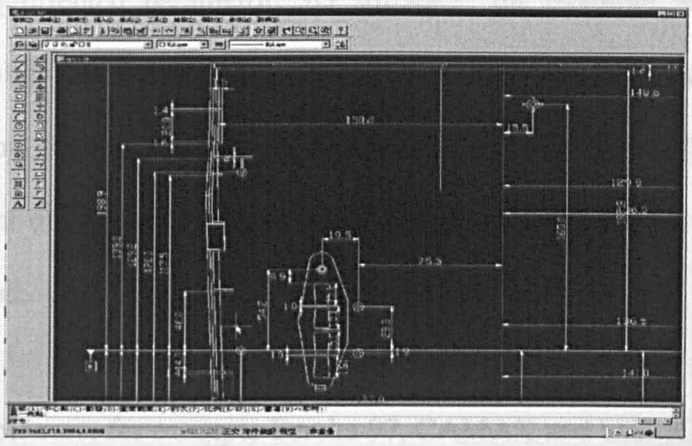

Figure 3.2: An engineering drafting in Auto-CAD

(2) 2D engineering drafting software: for example Auto-CAD, and MicroStation. This kind of software is mainly used in interior design, mechanical design, pipe engineering design, and product design. Figure 3.2, for example, is an engineering drafting in Auto-CAD. The major purpose of this kind of software is to manipulate the visual property of line elements colour and dimension. In Auto-CAD, a built-in program, Auto-Lisp, is offered to let designers speed up their design jobs using specially designed algorithms. For instance, the standard components or frequently used items are often constructed in blocks, which can be inserted into a drawing to save energy and time, and reduce errors.

(3) 3D CAD software: four categories can be classified according to their purposes.

A. 3D Models: for example 3D Studio, Alias, and Rhinoceros. Precise dimensions are not required in this kind of CAD software. They focus on the construction and generation of the product form.

B. Engineering-oriented parametric 3D software: for example Pro-Engineer, Ideas, Eureka, Solidwork, Solid Edge, and AMD. This type of CAD software places emphasis on the digitisation of the ideas and is suitable for the design and development of product structure. The weight and volume of every component can be calculated.

C. 3D CAM software: for example Eureka 97, CAMAX and UERICUT of IDEAS, and Solid Edge's CAM. This kind of software also has engineering-oriented characteristics where solid modelling structure is provided for production. CNC tooling or laser rapid prototyping can be easily transferred or revised for CAM systems.

D. 3D dynamic simulation software: for example Design Animation of the Mechanical design in Pro-Engineer and Performance-Driven Design. Such 3D software will make it possible for designers to observe the performance effectiveness and movement trace of a mechanical component. The strength and weakness of a mechanism, therefore, can be easily checked.

(4) 3D animation software: for example 3D Studio, Microstation. For industrial designers, the purpose of the animation is to offer different angles of views of a product. The Masterpiece of MicroStation, for example, uses the trace for moving the camera to control the change of views. In addition, the use of virtual reality enhances the visual effect and will offer a real sense of the space and size.

Among these CAD software packages, only some are used in industrial design. Because of the different design phases, different software is used in the design process. According to PC magazine (October 1997), the 2D software packages that are frequently used includes CorelDraw, Illustrator, and PhotoShop. Because vector drawings can be easy to change or extend, they help industrial designers a lot in developing the product form. In terms of image processing, PhotoShop offers the designers a lot of tools that can give a realistic look to the image. Texture tools are another feature that can make the image look like a real one (Figure 3.3).

Figure 3.3: A rendering of handy massager processed in PhotoShop

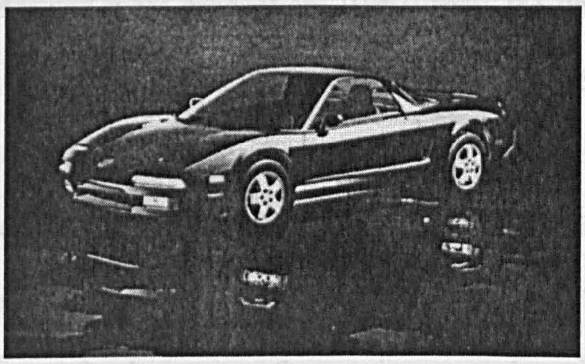

Figure 3.4: A car rendering processed in Alias

Among 3D CAD software, Alias is the industrial designers' favourite (Buckner, 1993). As can be seen in Figure 3.4, the image generated in Alias is almost like the real product and can be used for a catalogue or manual. The Timex company, for example, used Alias to colour and finish the surfaces of their product and produce a photo-real image (Houlihan, 1993). By doing so, the communication between the product designers and clients is improved.

One problem with Alias is that its file format is not compatible with other engineering software. To be acceptable for manufacturing, an Alias file needs to be converted. Lex Lennings (1992) used two design cases: a baby car seat and Hypex, an aid to stop hyperventilation, to explain how to transfer Alias files to SIPSURF, CAM software, so as to make a solid model.

As far as the integration of the above-mentioned CAD software is concerned, Harkius (1993) studied how to utilise design information with CAD tools in the design process. He came to the conclusions that designers can share design information through mechanical design automation (MDA). These data can be integrated, altered for engineering purposes and mass production. Particularly, the dimensional accuracy and model making can also be improved by the design integration. Sulek (1994) proposed a Virtual Design Studio as an example. Texas Instrument (TI) used the system in the idea development phase (Figure 3.5). It integrated marketing, design, and manufacturing. The design process was connected by an electronic network that also provided a communication channel for designers, other engineers, and customers. Figure 3.6 shows the design renderings for communication in the design process.

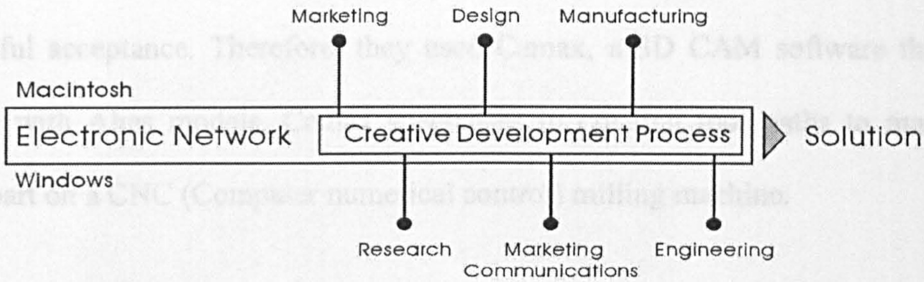

Figure 3.5: Texas Instrument's electronic network concept for design process

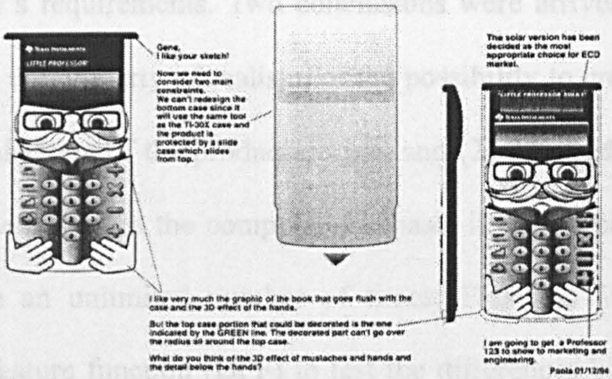

Figure 3.6: Design images for communication in TI's electronic network.

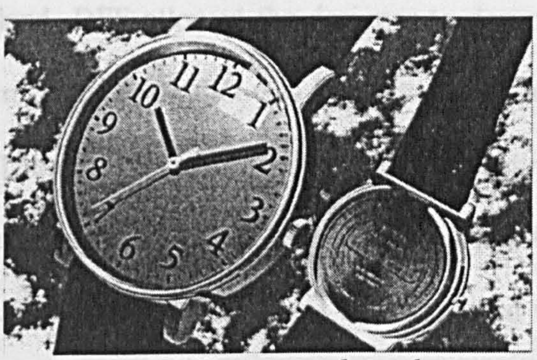

Figure 3.7: Timex watch rendering

Timex also employed 3D software to assist product design (Houlihan, 1993). They thought that a 3D representation was still necessary, especially for the case design itself. The computer (Figure 3.7) can simulate graphic details and colour options quite well, but for the scale, sculpture, and the style of the actual case, a mock up is critical to its successful acceptance. Therefore, they used Camax, a 3D CAM software that works directly with Alias models. Camax specialises in creating tool paths to machine an actual part on a CNC (Computer numerical control) milling machine.

Gerard Loosschilder (1994) used armchair as an example of a concept test. Based upon the interviewer's preference towards armchairs, he constructed 3D models to meet the interviewer's requirements. Two conclusions were arrived at in the study: (1) 3D models feature the property of realism, or the possibility to create a comprehensive and elaborate visualisation of the product design, and (2) 3D models have flexibility. Once the design is described in the computer database, it can be changed by modifying the data of design an unlimited number of times. Elas and Vergeest (1998) used the displacement feature function (DFF) to test the differences between other software by observing industrial designers who were experienced users of 3D software. The new function was connected to the Computer Aided Conceptual Design (CACD) of Delft University, Holland. DFF allowed the designer to design a displacement feature in a specific way. First, the region that was to be displaced had to be defined on the given surface model. The designer could sketch data points directly onto the surface (Figure 3.8). Once the designer had sketched the feature boundary, the corresponding displacement feature could be calculated and displayed within tenths of a second. As soon as the displacement feature was displayed, a window would appear with several sliders (Figure 3.9). Each of these sliders controlled one parameter of the displacement feature.

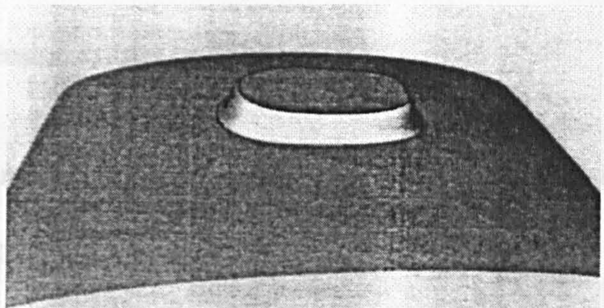

Figure 3.8: 3D shaded image of a protrusion. The feature boundaries are shown in black

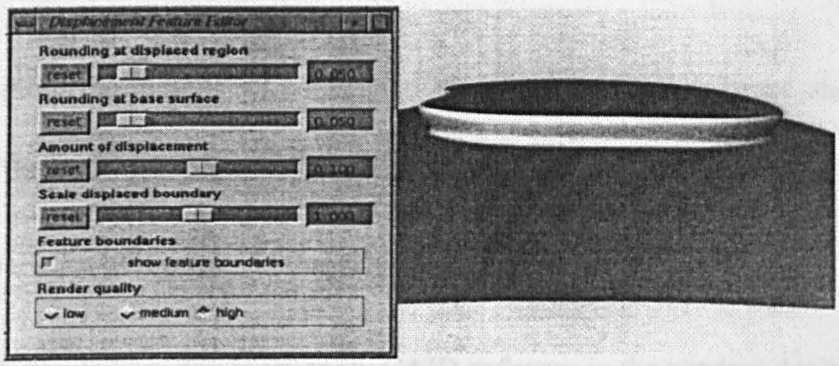

Figure 3.9: Sliders in the Displacement Feature Editor

There were sliders for the rounding of parameters, amount of displacement, and there was one slider that allowed scaling of the feature boundary to enclose the displaced region. Furthermore, the designer could, optionally, show the sketched feature boundary and the feature boundary that enclosed the displaced region. Using this dialog box, the designer could alter any parameter of the displacement feature by simply dragging the corresponding sliders to a different value. The DFF provided visual feedback cues, and the displacement feature was updated in tenths of a second. In this way, the designer had full control over the shape of the feature and fully interactive performance.

3.3 A Survey of CAID application in manufacturer's design department, design house, and design studio in Taiwan

To have an in-depth understanding of how industrial designers apply CAID software to their design activities and whether CAID software provides aids or generates new obstacles for industrial designers, the researcher made a survey of CAID application in Taiwan. Emphasis was placed on relationship between the design phases and the software used and between the software characteristics and the actual design activities. The objectives of this survey are listed below:

(1) To explore the reasons why designers choose to use the software and the relation between design activity and the application of the software.

(2) Comparisons of the effectiveness of CAID software.

(3) To investigate how designers apply CAID software in the product design process.

(4) To explore methodologies for using CAID software in developing new ideas.

(5) To examine the advantages and disadvantages of applying CAID software in developing ideas.

To reach an overall result, the subjects were chosen from in-house design departments in manufacturing companies, design houses, and design studios. These design groups vary in terms of their organisation, labour, and design work. The in-house design department in a manufacturing company needs to cooperage with other divisions for administration affairs. For example, there are a lot of interactions between marketing, sales, production, quality control divisions and the design team. Documents for communication in the management hierarchy may limit the flexibility and dynamics. The manufacturing company boasts sufficient financial resource, labour, and more importantly, multiple disciplines which can complement each other. The organisation of a design house is simpler because most of their employees are focused on product design. It features flexibility in professional communication and interaction. A lack of financial resource and different professional experts are their weaknesses. Design studios often consist of 1 to 3 team members. Flexibility and dynamics are their management feature in that they often cooperate with different companies for design projects. Limited financial resource is their weakness, too. However, the three groups of design organisations will work in different ways for design in the CAID environment due to their different workforce and financial supporting.

The survey also explored whether or not the characteristics of the above mentioned design groups would influence the methods and procedure designers used in applying CAID software in their design activities. Please refer to Appendix A for the content and format of the questionnaires. Raw data of 21 subjects (design organisations) out of 100 were gathered in the study. Please refer to Appendix B for the raw data.

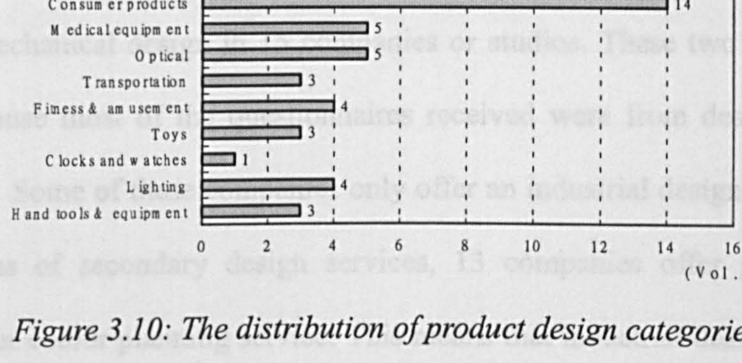

Figure 3.10: The distribution of product design categories

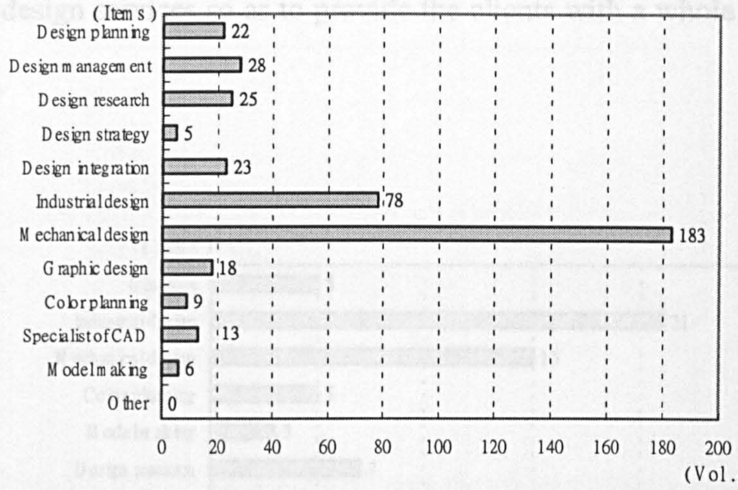

Figure 3.11: The distribution of design professions

According to the descriptive statistics of the raw data, the major categories of industrial design in Taiwan are the so-called 3C industries (computer, communication, and consumer products) (Figure 3.10). The distribution pattern is closely related to the manufacturing environment and financial structure of the manufacturing companies in Taiwan. Secondly, among the 21 design groups, the majority of designers belong to mechanical design (183) and industrial design (78) (Figure 3.11). This indicates that there is a close tie between industrial designers and mechanical engineers in designing and developing new products.

In terms of major design services, industrial design is offered in 21 companies or studios and mechanical design in 15 companies or studios. These two design services stand out because most of the questionnaires received were from design houses and design studios. Some of these companies only offer an industrial design service (Figure 3.12). In terms of secondary design services, 13 companies offer graphics and 6 companies offer colour planning service. This means that industrial design covers these two kinds of design services so as to provide the clients with a whole series of services (Figure 3.13).

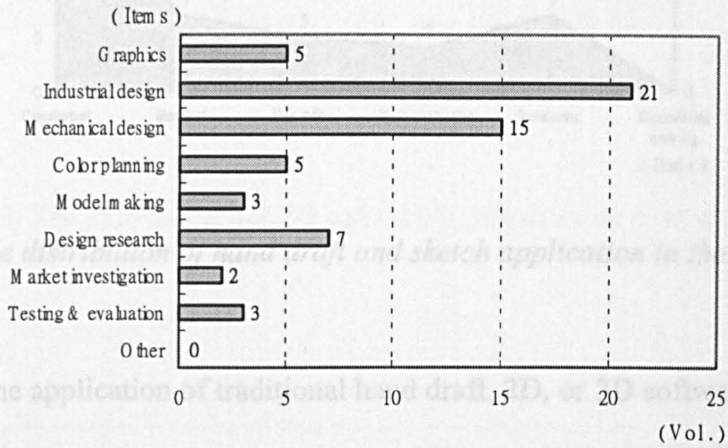

Figure 3.12: The distribution of major design services

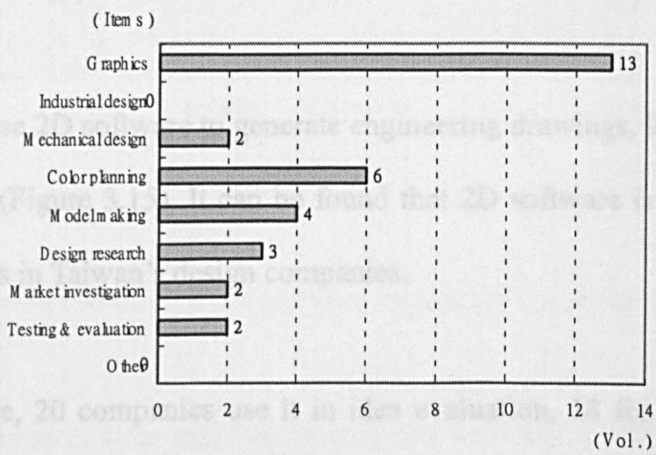

Figure 3.13: The distribution of secondary design services

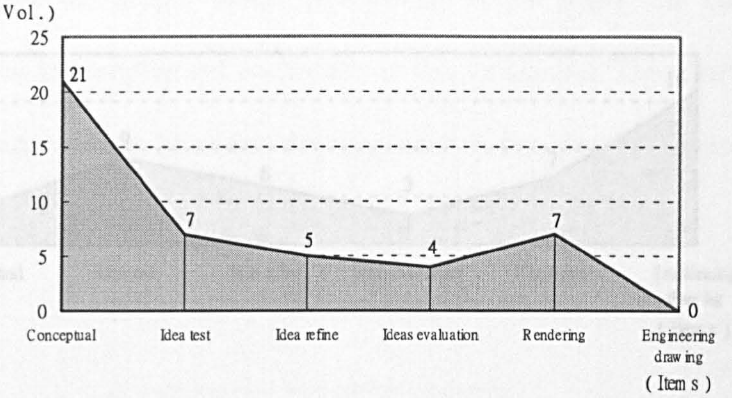

Figure 3.14: The distribution of hand draft and sketch application in the design phases

As far as the application of traditional hand draft, 2D, or 3D software is concerned, it was found that all designers use hand draft sketches to generate ideas in the idea development phase. Among them, 7 companies still use only hand draft sketches for idea testing (Figure 3.14).

16 companies use 2D software to generate engineering drawings, 9 for idea testing, and 7 for rendering (Figure 3.15). It can be found that 2D software is widely used for engineering drawings in Taiwan's design companies.

For 3D software, 20 companies use it in idea evaluation, 18 for idea refinement and rendering, and 17 for engineering drawings. Moreover, 13 companies use 3D software in the conceptual design phase and 11 for idea testing (Figure 3.16). Generally speaking, the distribution of using 3D software is similar in terms of all the design phases, which indicates that 3D software is powerful and can meet the requirements of the different design phases.

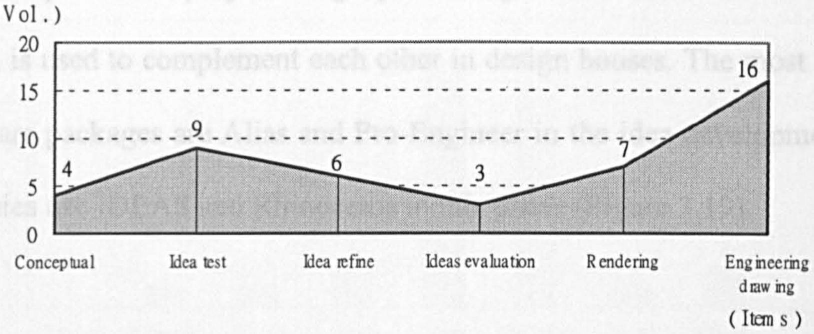

Figure 3.15: The distribution of 2D software application in design phases

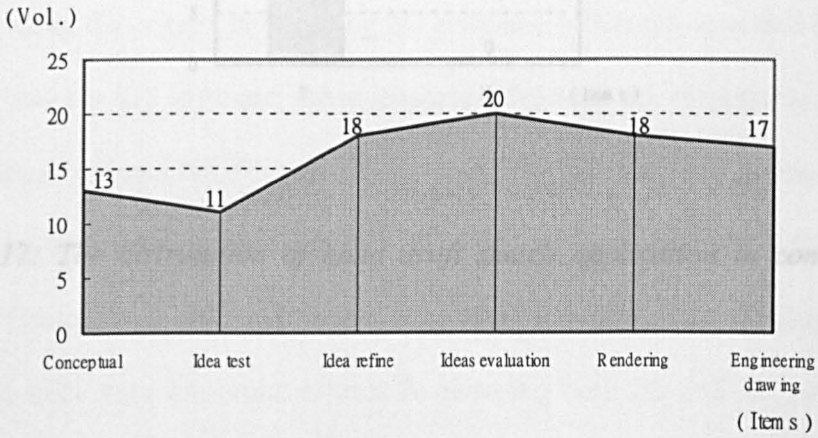

Figure 3.16: The distribution of 3D software application in design phases

In question 5, subjects were asked to identify the way they used these tools in the idea development phase. As can be seen in Figure 3.17, designers in all of 21 companies replied that they use free hand drawings in this design phase. This means that a skilled designer cannot do without the hand drawing. In terms of 2D software for idea development, 13 companies chose Auto-CAD, 7 chose CorelDraw, and 4 chose PhotoShop (Figure 3.18). The reason why Auto-CAD is popular is that it is used mostly in engineering drawings. Some of the Auto-CAD drawings are transferred to CorelDraw or PhotoShop for the proper image processing of the ideas. 2D software package, therefore, is used to complement each other in design houses. The most frequently used 3D software packages are Alias and Pro-Engineer in the idea development phase. Only 2 companies use IDEAS and Rhinoceros in this phase (Figure 3.19).

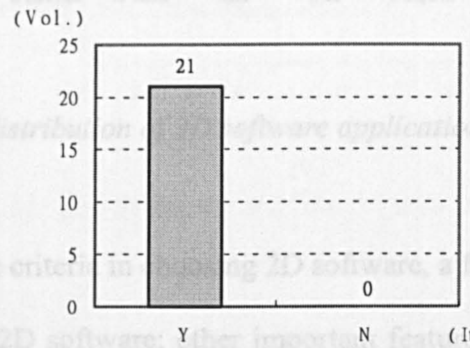

Figure 3.17: The distribution of hand draft sketch application in conceptual design phase

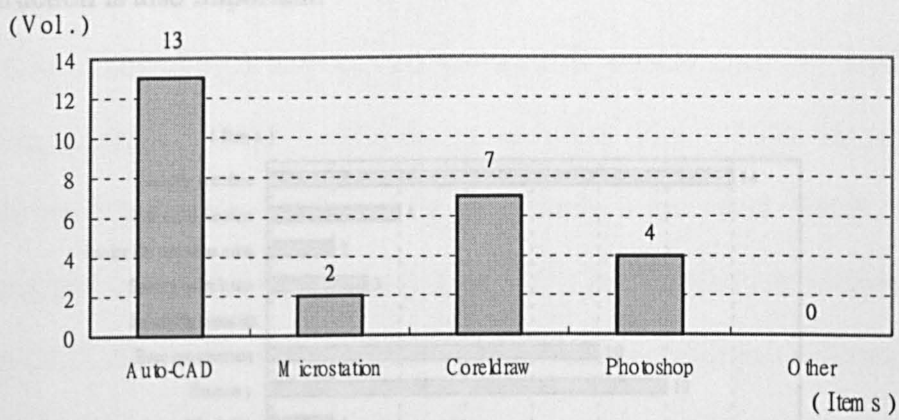

Figure 3.18: The distribution of 2D software application in the conceptual design phase

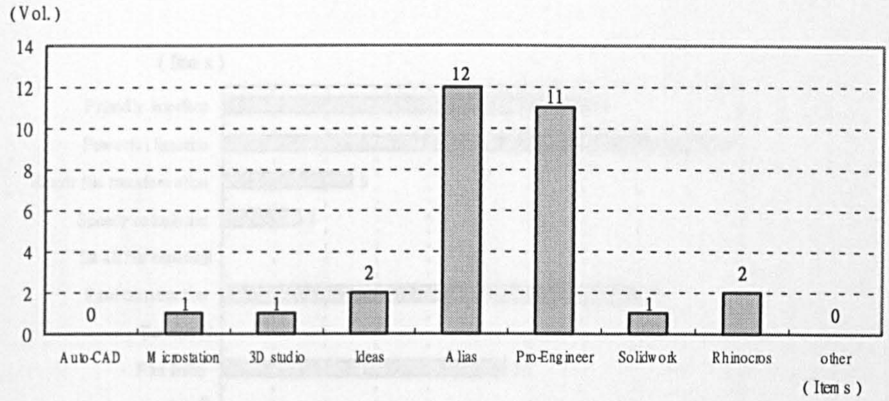

Figure 3.19: The distribution of 3D software application in conceptual design phase

Regarding the criteria in choosing 2D software, a friendly interface (14) is the most important one for 2D software; other important features are reasonable price (12), and ease of construction (10) (Figure 3.20). For 3D software, the average of powerful functions is the most important criteria (19), ease of construction (16), friendly interface (14), and flexibility (11) (Figure 3.21). The results indicate that a friendly interface is considered to be very important criteria in choosing both 2D and 3D software. Ease of construction is also important.

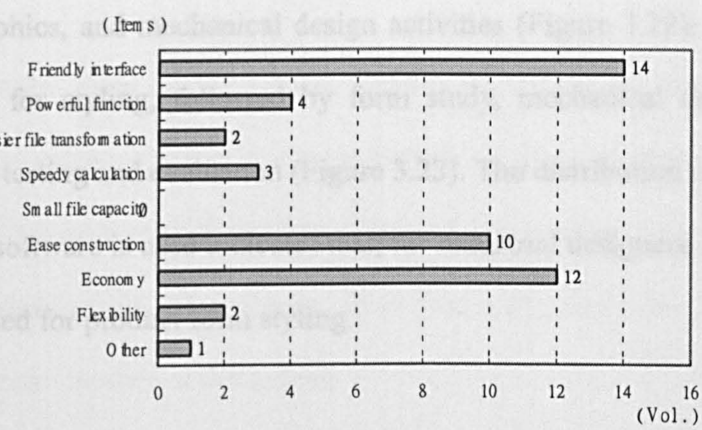

Figure 3.20: The distribution of the criteria in choosing 2D software

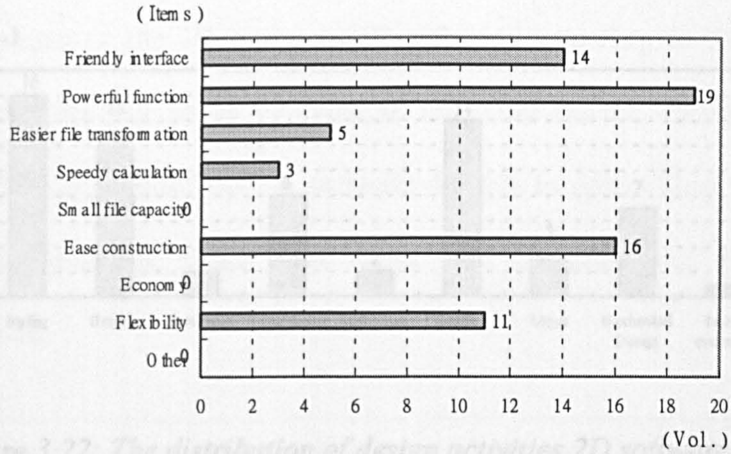

Figure 3.21: The distribution of the criteria in choosing 3D software

The differences between the criteria in choosing 2D and 3D software is that designers do not care as much about the range of functions in 2D software. On the contrary, a range of powerful functions is the criteria designers consider most in choosing 3D software. In addition, software flexibility is another criteria designers pay serious attention to.

Concerning design activity, 2D software is mostly used for styling, and then drafting, graphics, and mechanical design activities (Figure 3.22). 3D software is also mostly used for styling, followed by form study, mechanical design, visual media, drafting, and testing and evaluation (Figure 3.23). The distribution of design activities in which CAD software is used indicates that, for industrial designers, 2D and 3D software are mostly used for product form styling.

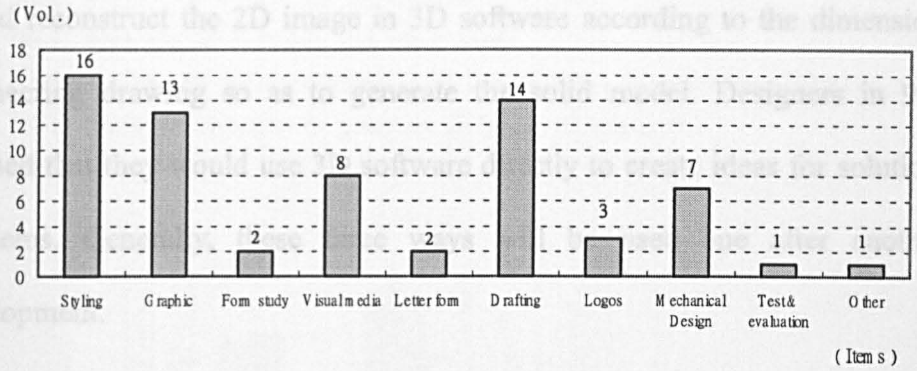

Figure 3.22: The distribution of design activities 2D software is used for

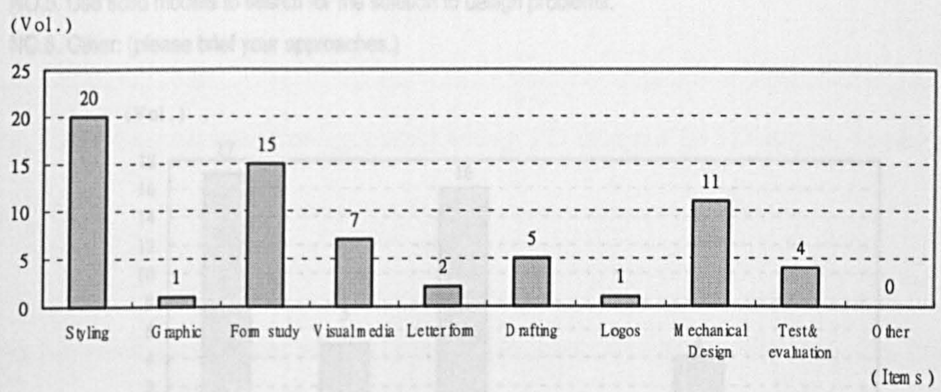

Figure 3.23: The distribution of design activities 3D software is used for

When asked about how designers transfer 2D images to 3D ones, most designers use 2D graphic software to create images directly on the computer or use 3D software to create a 3D visualisation of their ideas (Figure 3.24). Another way is to use digital pad to generate sketches in 2D software. However, some designers choose simple solid materials to make models of their ideas.

When the hand drafting sketches are done, most designers would scan the 2D image and trace the drawing to make 3D solid models (Figure 3.25). Alternatively they would reconstruct the 2D image in 3D software according to the dimensions in a 2D engineering drawing so as to generate the solid model. Designers in 9 companies claimed that they would use 3D software directly to create ideas for solution to design problems. Generally, these three ways will be used one after another in idea development.

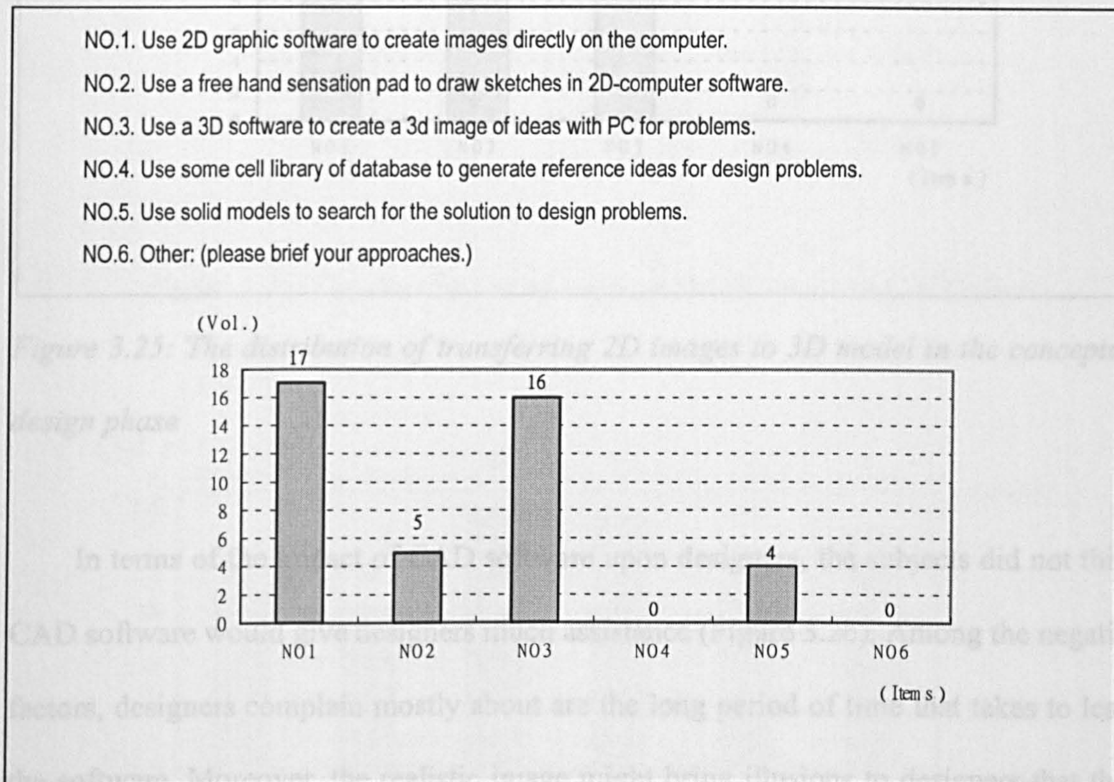

Figure 3.24: The distribution of CAD system application methods in the conceptual design phase

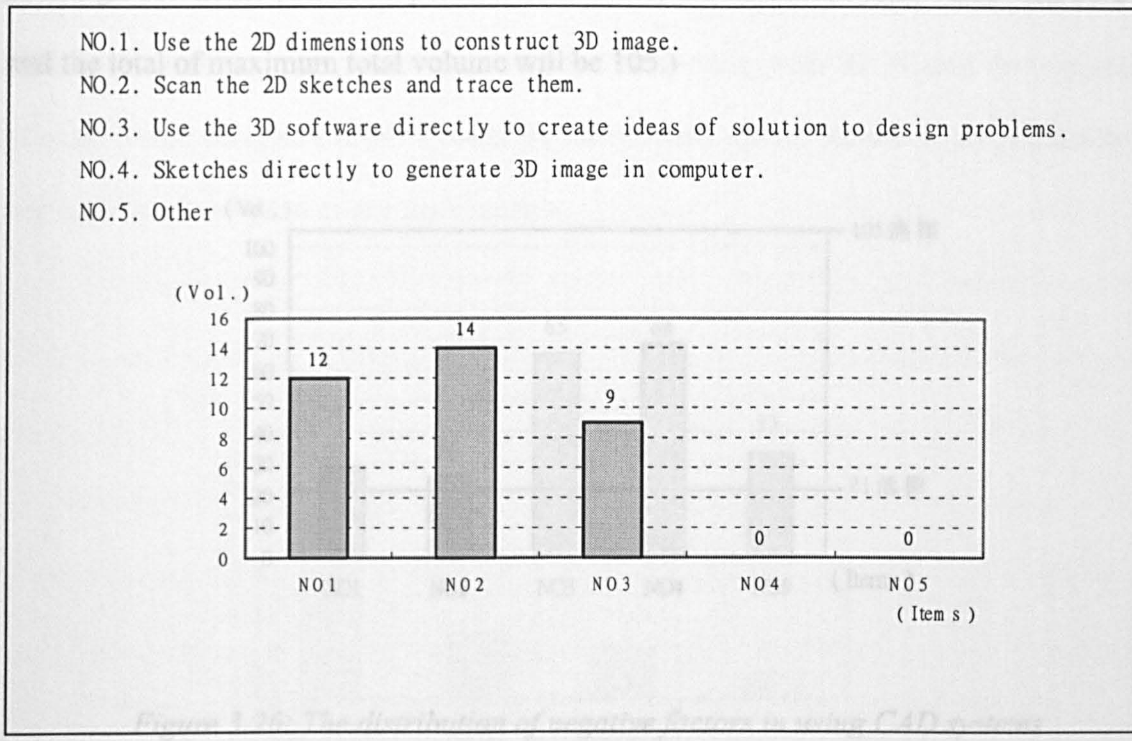

Figure 3.25: The distribution of transferring 2D images to 3D model in the conceptual design phase

In terms of the impact of CAD software upon designers, the subjects did not think CAD software would give designers much assistance (Figure 3.26). Among the negative factors, designers complain mostly about are the long period of time that takes to learn the software. Moreover, the realistic image might bring illusions to designers that they have created a perfect idea. Most of the subjects do not think that the use of CAD software will hinder their creativity in idea generation. In terms of the positive factors, most designers consider CAD software important for the realistic images of ideas, speeding up the design process, reducing errors, and producing better design quality (Figure 3.27). Finally, the subjects do not think that the application of CAD software will increase the number and creativity of ideas. In other words, the use of CAD software at current time does certainly not benefit designers in the variety and creativity of design solutions. (On the 5-point attitude scale, the minimum total value will be 21 and the total of maximum total volume will be 105.)

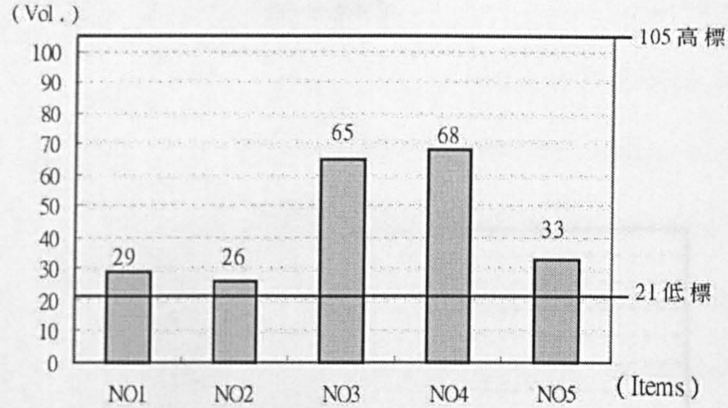

Figure 3.26: The distribution of negative factors in using CAD systems

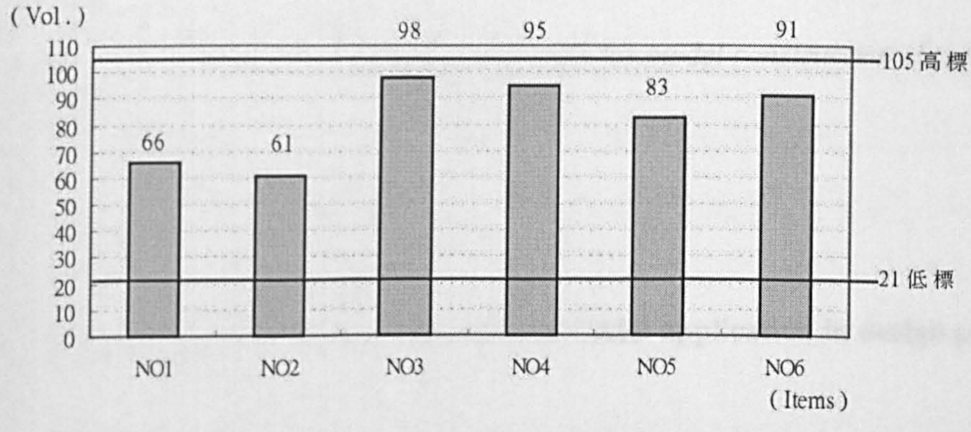

Figure 3.27: The distribution of positive factors in using CAD systems

Beside 2D and 3D CAD software, the results also indicated that designers did not use other types of software to help generate design ideas (See Appendix B). Only 3 companies out of 21 once attempted to use Director to simulate the motion of the human body to help with their product design.

Lastly, the distribution of CAD system classifications (Figure 3.28) shows that CNC machines are mostly used to produce solid models, with RP (Rapid Prototyping) second. Some designers make models by hand, while others choose to use both CNC and hand made ways to create their models.

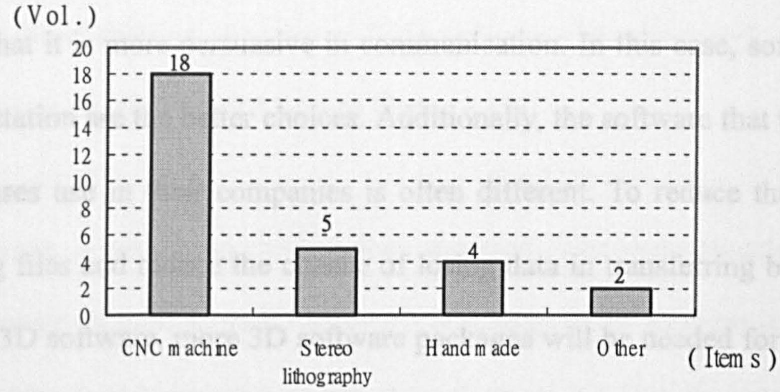

Figure 3.28: The distribution of tools for model construction classifications

3.4 The follow-up face-to-face interview of CAID application in design process

From the raw data of the survey, some impact questions were raised. To find the answers to these questions, the researcher interviewed the subjects face-to-face.

1. Why did one the subjects (Subject 12) use four 3D software packages: Microstation, Alias, Pro-Engineer, and Rhinoceros?

It was because the design house has contracts with many companies whose products are different in terms of form features. Some of them are geometric and can be generated in the engineering-oriented 3D software such as Pro-Engineer. Other products have all sorts of curvatures and constructing these models would be difficult in the same 3D-software package. Software that has powerful surface functions like Rhinoceros and Alias would be more suitable. Sometimes the clients require a much more realistic image so that it is more persuasive in communication. In this case, software like Alias and Microstation are the better choices. Additionally, the software that the clients of the design houses use in their companies is often different. To reduce the problems with transferring files and reduce the chance of losing data in transferring between different formats of 3D software, more 3D software packages will be needed for different design projects. As the interface design of Rhinoceros is close to that of Auto-CAD, which is the most popular 2D software in Taiwan (Figure 3.18), it is easy and fast to learn. Moreover, it can be transferred to many 3D formats such as Pro-Engineer, Alias, and IDEAS. Rhinoceros, therefore, is often used with other 3D software. The surface of a product can be constructed in Rhinoceros and then turned into a solid model in Pro-Engineer for engineering design and output.

2. Why did many of the subjects use hand draft sketches, 2D software, and 3D software in the idea development phase (Figures 3.17-3.19)?

Not all-industrial designers are familiar with these three tools. Some who are not adept at hand drafting sketches will choose to use 2D software such as CorelDraw or Illustrator for their idea development. On the contrary, other designers that are adept at hand drafting skills but not at CAD systems will develop ideas by free hand sketches directly. There are still others designers specialising in all three tools. They would choose the most suitable tool in accordance with the property of the product form. They tend to use 2D and 3D software for their ideas in order to provide for the decision-makers through high-quality presentations. Generally companies do not limit the tools and methods designers use in idea development so as not to hinder their creativity.

3. Why are hand drafting sketches and 2D software most frequently used in the idea development phase (Figure 3.14 and Figure 3.17)?

This answer is similar to the previous question. The main reason is that it takes longer to construct models in 3D software, resulting in the low use of 3D software in idea development. Additionally, in the early stage of the idea development phase, the need to refine or reject ideas to improve the design quality is high and it is difficult to revise the ideas constructed in 3D software. The designers, therefore, are not willing to use 3D software for idea development at the beginning. It would be applied however if the designer needed to produce a more realistic image for the decision-makers to accept his or her ideas right at the beginning.

4. Why do design companies use more than 3 methods to transfer free hand sketches to 3D computer models (Figure 3.25)?

The reason why design companies will use more than 3 methods to transfer free hand sketches to 3D computer models is that the tools designers use in idea development are different. Consequently, the ways of transferring free hand sketches to 3D computer models are not the same. To produce the mechanical design later in

3D software, the supervisor will often want more concrete output data because the views in 2D software do not necessarily accurately present the details of a product form, especially the subtle change of curved surfaces (Figure 3.29). In Figure 3.29, the views may seem to meet designer's aesthetic requirement and manufacturing needs, but a close look will show that the change in the curve surfaces are not consistent. The conjoining curvatures cannot be constructed. Only after the simulation of a possible form by a senior designer through hand draft sketches (Figure 3.30) and again Pro-Engineer (Figure 3.31) can a complete product form with detailed 3D solid model be achieved. If the designer is only familiar with 2D software and not 3D, some problems can occur unless he or she is careful in dealing with the subtle change of the curves of the product form.

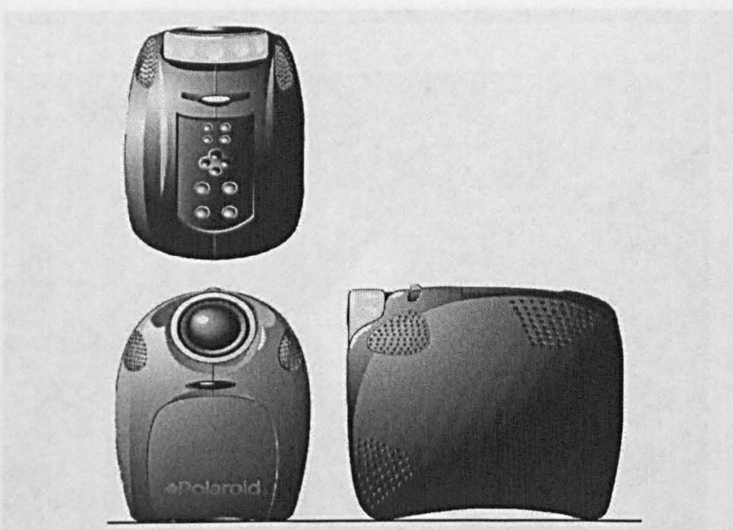

Figure 3.29: A 2D rendering of an LCD projector created by the CorelDraw software

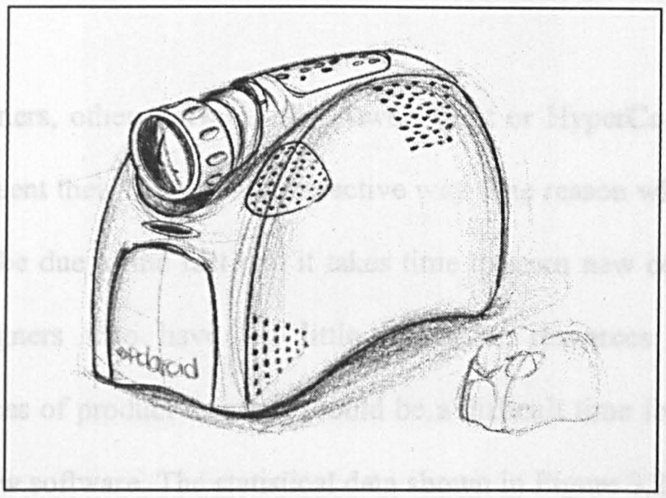

Figure 3.30: A hand draft sketch made by a senior designer according to the 2D rendering in Figure 3.29.

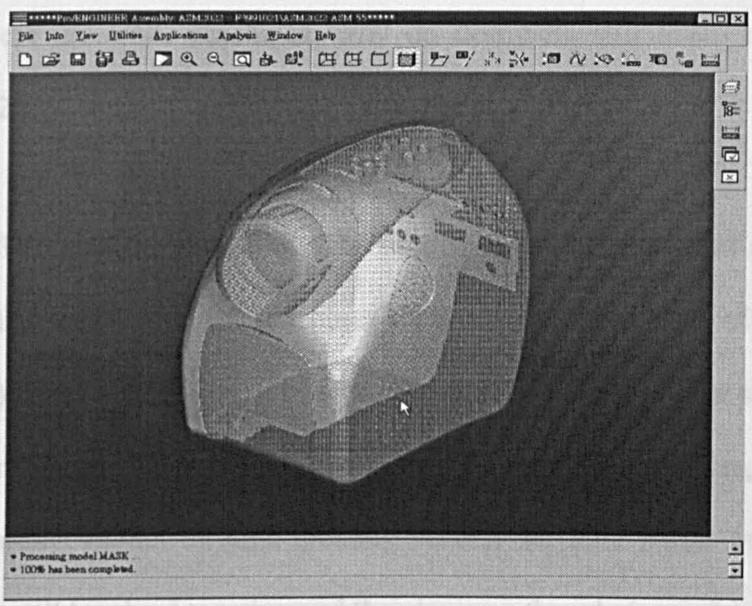

Figure 3.31: A 3D model constructed in Pro-Engineer according to the 2D rendering and hand draft sketch in Figures 3.29 and 3.30.

5. Why do few companies use software other than 2D and 3D software?

For product designers, other software like Power Point or HyperCard can be used to help designers present their ideas in an interactive way. The reason why this software is seldom used may be due to the fact that it takes time to learn new computer software. For product designers who have too little power or resources to construct the complicated surfaces of product forms, it would be a difficult time for them to have to learn additional new software. The statistical data shown in Figure 3.26 indicated that it is indeed time-consuming to learn CAD software. Finally, this also means that, in addition to the CAD software, other software that can assist product designers present their ideas or communicate with the clients are badly needed.

6. Since there are CNC machines, why do designers still make models manually (Figure 3.28)?

Though CNC machines are frequently used (Figure 3.28), manual model making is still important. Sometimes CNC machines are applied to the tooling of a simple surface (Figure 3.32). However, if the side or some small detailed part is too small for the tooling cutter, hand-made tooling is the better choice. Model makers, therefore, often develop a product model through creating several separate parts. After each part is finished, they will be glued together and then become the whole model.

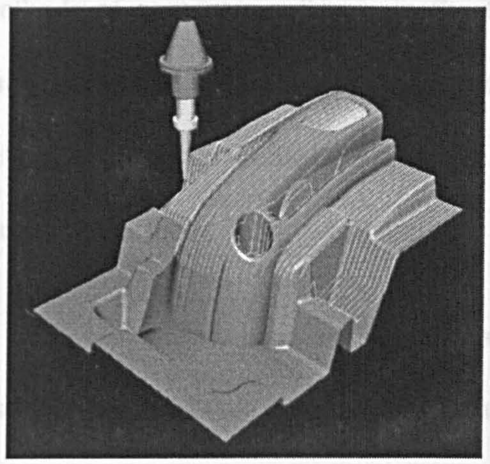

Figure 3.32: The CNC machine tooling just for a single side

7. Why are RP systems not frequently used in model making (Figure 3.28)?

Though the model made by a RP machine is solid and strong, the accumulation forming will lead to a rough surface with layers of forming material that does not satisfy the finish required of most products. Furthermore, it takes time and money to treat the finish. To make the matter worse, it is expensive to buy a RP system. The result is that RP systems are far less popular than CNC machines.

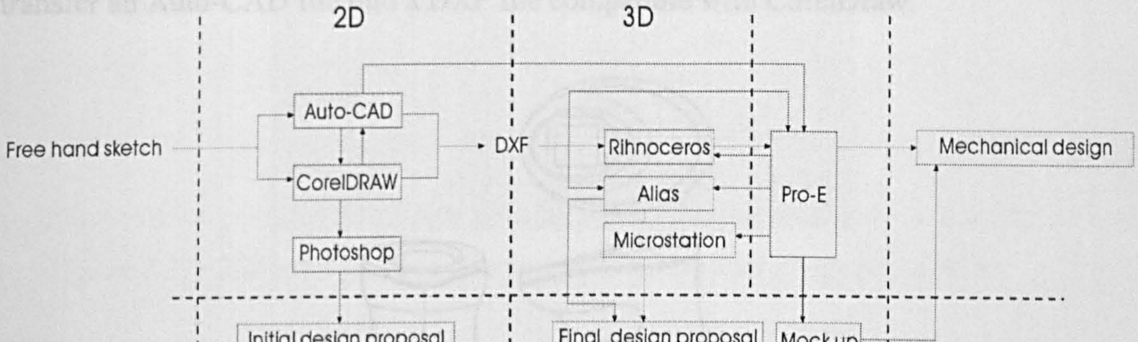

Figure 3.33: The design process and CAID software application (Subject 12)

The application methods of computer software in the CAID design process can vary. Subject 12 is a design house using four different 3D software packages. As can be seen in Figure 3.33, such kinds of design companies possess more flexibility in design process. The reason is explained in the following section.

In most cases, free hand sketches are used in the early stage of idea development phase in the design house of subject 12 (see Figure 3.33). When some initial results are reached, CorelDraw will be used to construct the profile structure (Figure 3.34). Through discussion and refining, the coloured blocks in the CorelDraw file (Figure 3.35) will be transferred into PhotoShop in an AI format where the product rendering will proceed for presentation of the design proposals (Figure 3.36). If a design alternative is chosen by the client, the CorelDraw will then be transferred into Rhinoceros, Alias, or Pro-Engineer in a DXF format to produce surface a model or a solid model. If Pro-Engineer or Rhinoceros is chosen, the final 3D file needs to be rendered in Microstation or Alias for a high quality product image (Figure 3.37). It is up to the designer to choose the 2D software. Both Auto-CAD and CorelDraw files can be transferred into DXF or AI format compatible with PhotoShop. Another option is to transfer an Auto-CAD file into a DXF file compatible with CorelDraw.

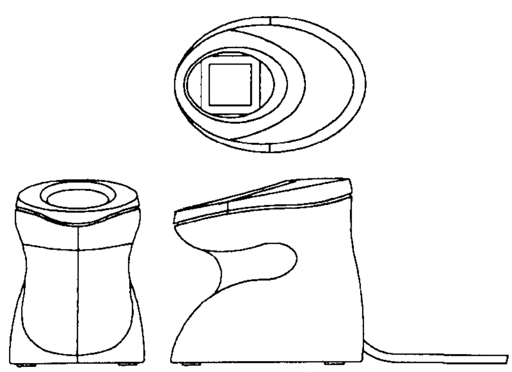

Figure 3.34: Three sides vector views of a fingerprint reader in CorelDraw

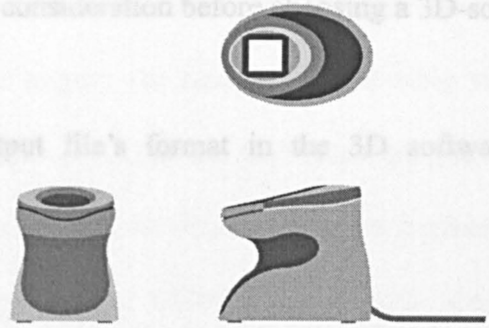

Figure 3.35: The colour blocks of a fingerprint reader in CorelDraw

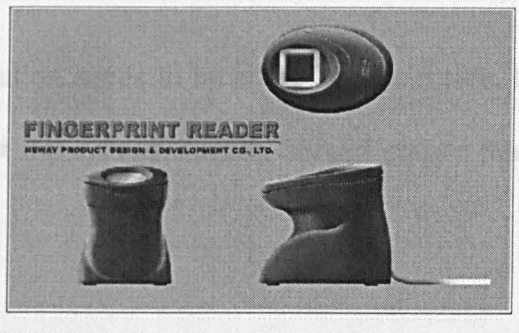

Figure 3.36: The rendering image of a fingerprint reader in PhotoShop

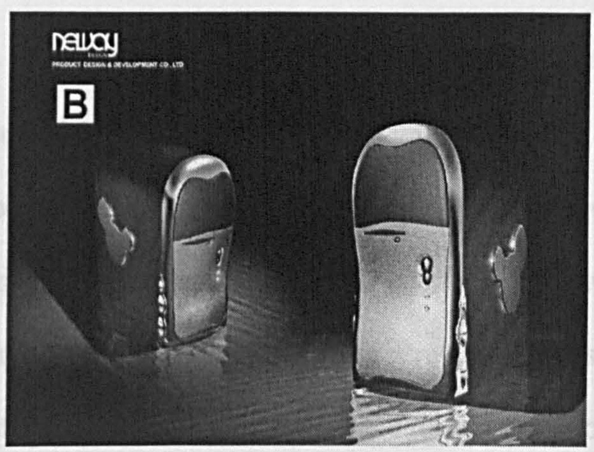

Figure 3.37: The solid presentation image of a personal computer in Alias

The selection of 3D software should consider the need for a smooth transition to future mechanical design. As Pro-Engineer is the most popular 3D software in Taiwan, it is often used to transfer the preliminary product design file. Four factors, therefore, should be taken into consideration before choosing a 3D-software package:

(1) Whether the output file's format in the 3D software is compatible with Pro-Engineer?

(2) Which 3D-software package can guarantee a faster and more efficient way for constructing the curved surface?

(3) If the design solution needs to be altered in the future, the 3D software parameters used to construct the curved surface, should ensure that are compatible with Pro-Engineer.

(4) Whether or not the shielding of the curved surface constructed in the 3D software can be implemented into Pro-Engineer for mechanical design?

Sometimes it is not possible for designers to construct a subtle detailed curved surface in some kinds of 3D software. Other software, therefore, should be adopted to carry out the job. To solve this problem, some design companies would use Rhinoceros and Pro-Engineer one after another. Finally, a 2D engineering drawing with dimensions of the product form should be generated from Pro-Engineer so that designers can control the quality of the product form and examine the precision of the product form.

Some designers will generate solid models in 3D software directly from the free hand sketch to meet the pressure of a tight schedule. The design process in this CAID approach is shown in Figure 3.38. The designers use the Pro-Engineer to create the 3D model and then conduct the mechanical design in the urgent design projects. If the design project is not urgent, the designers used Alias to create the high quality 3D images as design proposals. After the clients accept one of the design proposals in an Alias file, it was transferred to Pro-Engineer to perform the mechanical design. In Taiwan, most enterprises are OEM (organisations working to specification only) manufacturers. It is, therefore, important for a company to let the buyer see the realistic image of their design proposal in advance. In this way, they will have the upper hand in winning the contract. For most design companies, their objectives are in making efforts to achieve a high quality design solution in a shortest period of time. Sometimes, even the free hand sketches will be omitted and 3D software, such as Alias, will be used directly to meet the client's requirement. In this case, however, the possibility for designers to adjust the design in later stages is much lower.

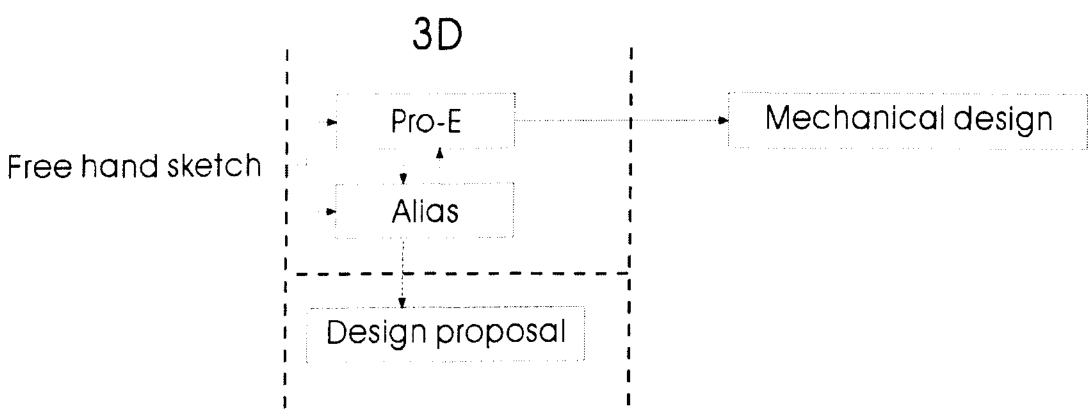

Figure 3.38: The CAID design process where free hand sketches are used for constructing solid models in 3D software (Subject 12)

According to the distribution of 3D software applications in the conceptual design phase (Figure 3.39), Alias and Pro-Engineer are the most popular (see conclusion of Chapter 3). There are no remarkable differences in preference between in-house design departments, design houses, and design studios.

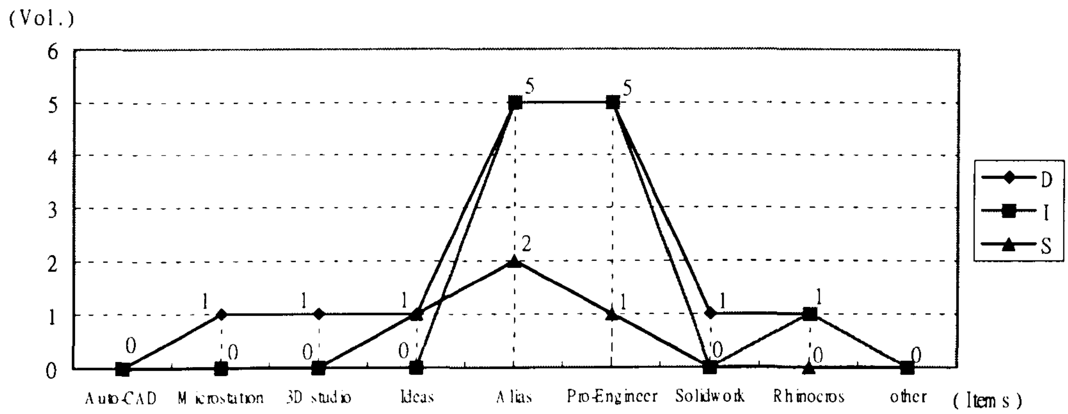

Figure 3.39: The distribution of 3D software application in conceptual design phases in design houses, in-house design department, and design studios

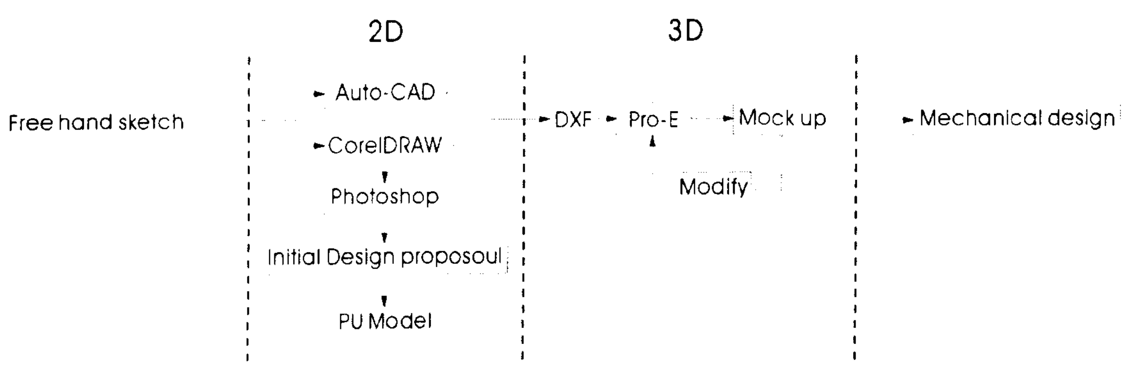

Figure 3.40: The CAID design process of a famous scanner manufacturing company (Subject 1)

Among those interviewed in design companies, Subject 1 is the industrial design department of a world famous scanner manufacturing company. The only 3D software they use is Pro-Engineer. They do not have any other 3D software for advanced rendering. The CAID design process of this company is shown in Figure 3.40. In the idea development phase, free hand sketches are the major tools. The images created in

2D software, like Auto-CAD and CorelDraw, are processed in PhotoShop for presentation. After idea screening, one or two alternatives will be chosen to make PU model to help verify the decision-making. After the ideas are confirmed, the idea will then be transferred into a 3D solid model in Pro-Engineer where a CNC machine in the model shop will generate the mock up. When the final design is specified, the Pro-Engineer file will be transferred for mechanical design. This process skips the step of rendering in 3D software because the manager in the design department thinks that the decision-makers (senior industrial designers) are familiar with product form. The physical PU models are used models instead of realistic 3D images as communication media for presentation. Though it takes more time and money to make physical models, the ability to touch the physical objects can give a better feeling of the size, thickness, as well as the possible operation. The manager points out though that this process might not be successful if the design project is really tight-scheduled would not meet the buyer's requirements in terms of time. In such case therefore, a high quality rendering using software, such as Alias, can be used to enhance the economic effectiveness and save time. In terms of the application of 3D software, designers sometimes need to compromise with 3D software and alter their ideas because it is too difficult to generate the required smooth curved surface in Pro-Engineer. As a matter of fact, it is probably not all the fault of the software. The designer, who uses Pro-Engineer, might not familiar with the characteristics and algorithms of the software. The users of the software, therefore, need to advance themselves and share with other peers their experiences in using Pro-Engineer.

Figure 3.41 shows the CAID design process of a design house (Subject 10). Free hand sketches are used in the early idea development phase. The refined sketches will be transferred into 3D/Paint by a digital pad for colours and rendered in CorelDraw or PhotoShop. Based upon the 2D drawing, a simple PU model will be used for product form checking before the solid model is made in IDEAS. The solid model generated in IDEAS will then be transferred to Pro-Engineer for mechanical design by the Step format. Sometimes the IDEAS model will be developed directly from the hand drafting sketches if the schedule is tight. Because IDEAS is not powerful at rendering, they will transfer the file to 3D MAX through Rhinoceros for the ray tracing, texture, and text mapping. Some designers will use Solidwork's Photowork to render their ideas if they are not familiar with 3D MAX.

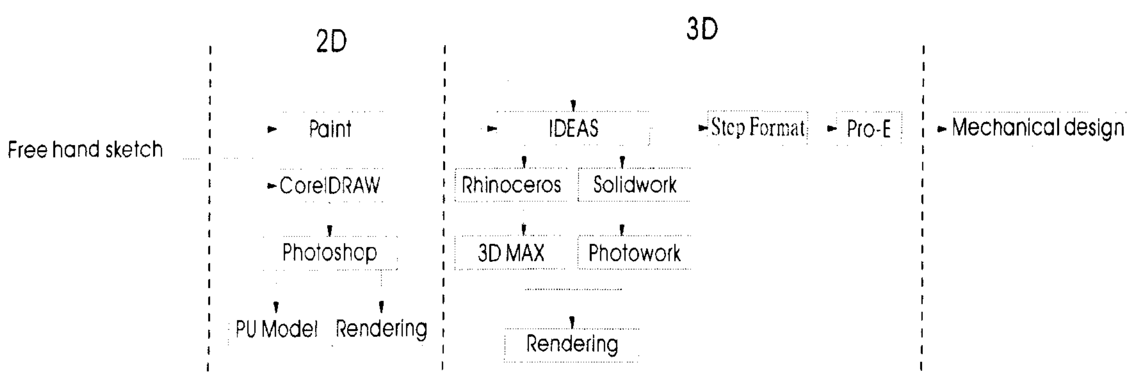

Figure 3.41: The CAID design process of a design house (Subject 10)

The other subject, the researcher interviewed personally, was a design studio (Subject 21). The designers in the studio were very young and familiar with Alias. In addition to product design, they also offered the service of Web-Home Page design and 3D animation for advertising. In the studio, designers were not confined to any given CAID process. They chose to work in the way they preferred. There were, however, two points that these designers had in common. First, they used free hand sketches for the early idea development because it gave them more freedom in expressing their imagination. A piece of paper and a pencil gave them everything they needed. Secondly, the final 3D product form was transferred into Pro-Engineer or another 3D software package for the client to construct later engineering design (mechanical design). The CAID process of this design studio is shown in Figure 3.42. Furthermore, they don't use 2D software to present their ideas because they don't think 2D drawings can accurately reflect the real properties of the product ideas. Due to the drawing skills and comprehensive use of lighting and shadows of the designer, the images on the drawings might be some mistakes. The 3D models are precise in presenting colour, finish, and texture. The final 3D file can be transferred for mechanical design without losing any details. Therefore, they consider the construction of solid models in 3D software as the essence of idea development that will speed up the design process.

The designers in the other four companies also confirmed this. They came to the conclusion that the details of product form would not be identified until the 3D solid model was built. 2D drawings do not precisely present the subtle details of their ideas. It is, therefore, often the case that designers will find it is necessary to revise or even reject the product form in 3D models. The visual properties described in 3D software would clarify any contradictions in 2D drawings.

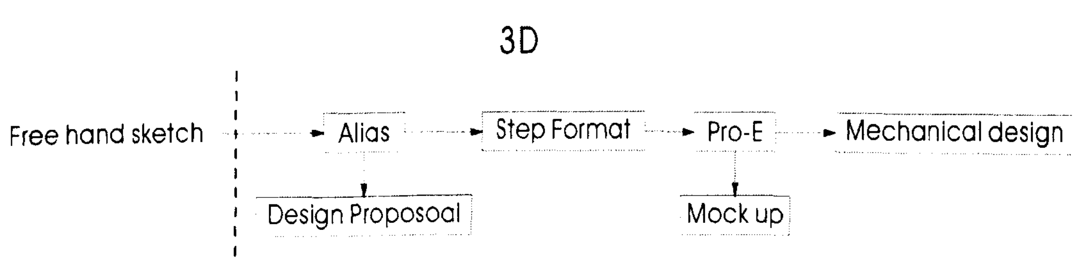

Figure 3.42: The CAID design process of a design studio (Subject 21)

Finally, professional CAD operators are sometimes needed because some product designers might not be fully familiar with the CAID software. This is the situation with Subjects 10 and 21. With the help of CAID experts, product designers can completely explain their creativity in generating ideas without worrying about how to manipulate the computer software.

The flexibility designers have in several kinds of CAID system application is a surprising find from the survey. For both 2D and 3D software, most companies will not use only single CAID software package. Because of the different requirements from the clients and different specifications of the computer systems, different CAID software will be chosen as appropriate.

3.5 Summary

The results of the survey show that CAID systems have been fully applied to the design process in design companies. Most designers have positive attitudes towards the application of CAID systems. The results indicate that CAID systems can speed up the design process, improve the design quality, and enhance the client's confidence and degree of satisfaction. The only factor that worries designers is that it takes time and energy to learn a CAID system. Special training is necessary for designers to master such computer skills. Meanwhile, designers do not think CAID systems will enhance the creativity and variety of their ideas. The most important criteria in choosing CAID systems are the friendly interface and the ease of constructing models. In addition, the researcher came to the following conclusions:

(1) More than one CAID system is needed to effectively solve the model construction and file transfer problems. This problem will occur in using 2D and 3D software.

(2) The familiarity and preference of the individual designer determine the selection of CAID systems. The manager would not constrain designers to use specific CAID software.

(3) The final product file, no matter what CAID system is used, should be acceptable to the engineering-oriented software for the purpose of mechanical design.

(4) The application of CAID systems in the product design process has the characteristics of flexibility and freedom, even though the individual designer's preference and the limits of the software mainly determine it.

(5) In addition to the use of CAID systems (2D and 3D), free hand sketches are the most common tool and method that designers use to develop their ideas in the initial idea development stage.

(6) It is necessary for a company to have professional CAID system operators that can work together with product designers for the product form design development, if the designers are not familiar with the CAID system.

(7) The most frequently used 3D software for refining ideas in Taiwan includes Alias,

Pro-Engineer, Rhinoceros, and Ideas.

(8) The most frequently used 2D software for refining ideas includes CorelDraw, PhotoShop, and Auto-CAD.

(9) Most designers consider the construction of 3D models to be the final stage for product form verification. It is also a better way to control the quality of product forms. Most refining and improvement to product form happens in 3D-model construction in which it is possible for designers to revise their ideas.

(10) Without the CAID operator's help, product designers should master more than one CAID software. They should spend more time learning new CAID systems so as to conduct their design activities smoothly and improve the design quality. Different software can be tried if they cannot fulfil their ideas in certain CAID systems.

(11) CAID system designers (engineers) should improve the interface design and methods for model construction according to the product design process and designer's habits, to reduce the learning time and improve effectiveness. Efforts should be made to enable product designers to make the most of the software's functions.

According to the above conclusions, several comments about the current range of CAID systems can be inferred. There are some weaknesses in the CAD and CAID software, which need to be improved.

(A) The definition of the construction commands needed in constructing the complicated curvature is not always clear and should be followed in a specific order. This will let product designers conduct model construction in a specific order in CAID systems

(B) Though most 3D software has powerful functions, even the designers or CAD operators that are familiar with them are not always able to fully explain their functions.

(C) The formats for most 3D software are not consistent. The detailed steps in transferring a 3D file should be made explicit to the operator. Otherwise, there will be errors in the file. For example, some small cavities between curved surface components are often seen.

(D) There should be a strict international standard of format for CNC machining and 3D CAID files. The current standards cannot solve such a problem.

Chapter 4 Examination of tools used in Idea Development Stage

4.1 Introduction

A preliminary experiment will be proposed in this chapter that based upon the results from the literature review and the state-of-the-art of CAID systems in Chapter 2 and Chapter 3. From the methods of 3D model construction mentioned in Chapter 2 and the application procedures for CAID systems mentioned in Chapter 3, it is clear that designers use traditional hand drawing as the main idea generation tool first and make initial refinement to their ideas in 2D software or scan the drawings to make 3D models. This design procedure where three tools are used can often be seen in practical design cases and appears to be a satisfactory.

In this study, the researcher attempts to explore the effect of CAID tools on the design activity by comparing the results between using and not using CAID tools in the design procedure. In this way, it is hoped the way designers apply CAID tools will be understood. These three tools, hand drawing, 2D and 3D software will be used separately by three different designers. The results obtained will serve as the basis for later research in Chapter 5.

To make it easy to perform the empirical investigation, the application of current computer package software, including 2D and 3D, is chosen for this research (please refer to Table 4.1 for these computer software). Because those tools are easy to access in design house, the researcher uses them as the software packages to conduct this test in this study.

2D	3D
Auto-CAD CorelDRAW Photoshop	Microstation

Table 4.1: The package of computer software

4.2 The case study

Due to the three different designers can go with this test faster and smoothly, the design project used in this study that should be not too complex of a product. The researcher decided that a car driving assistant device for the handicapped (Figure 4.1), that was developed by Neway Design, was used as a case study for empirical observation and analysis. The objective of the design project was to derive an appealing appearance for the product and make driving a car easier. The precedent product has a plastic handle equipped with an internal metal part. With the handle joined to the metal axis of the fixation stand, the driver can turn the handle by a single hand.

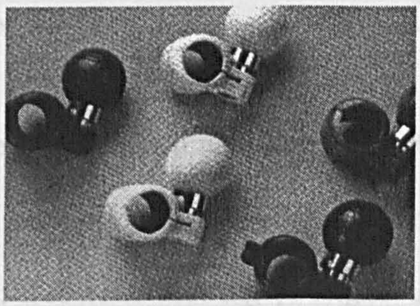

Figure 4.1: The original design of the driving assistant device

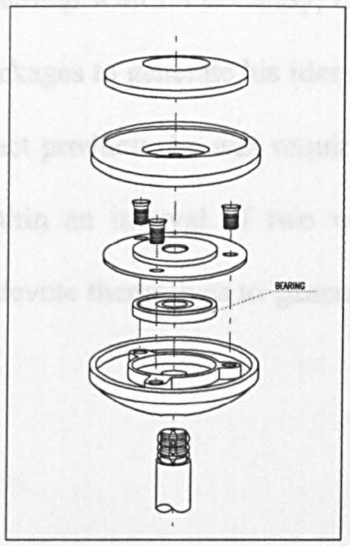

Figure 4.2: The exploded drawing of assistant driving device

After doing structure analysis and design, a more expensive bearing was adopted to replace the original turning mechanism to enhance its flexibility because the product is targeted for the high price market segment. Moreover, the addition of an aluminium die casting component to support the axis can increase its weight. Furthermore, it makes the turning stable and flexible, and reduces noise in operation (see Figure 4.2). When the new structure was decided, efforts were made to simplify the product form. A more detailed set of criteria for this project can be seen in Appendix C

Although in the present design process, the conventional tools and CAD system are already used, to make it easy for observation and comparison, three designers were assigned different tools: free-hand drawing (Designer A), 2D software (Designer B), and 3D software (Designer C). The three designers have the same experiences in industrial design for 3 years in Neway design. Designer A was required to use traditional hand drawing tools for idea development. Designer B who was familiar with

2D-computer software (PhotoShop with EYE-Candy, CorelDraw, and Auto-CAD) was required to use only these packages to generate his ideas. Since Designer C was good at using 3D software to construct products, he was required to employ only tools of this category (Microstation). Within an interval of two weeks for design project, these designers were able to fully devote themselves to generating any product form that met the requirements.

4.3 Empirical observation

The purpose of the empirical observation of the design activity was to compare the differences among these groups in terms of the design process, the output, and the variety of design. Special attention was paid to analyse these designers' design processes in idea development, the application of design tools, and the way the tools affected their design procedure. All sketches, no matter how simple or rough, had to be saved during idea development stage, which meant the designers who used CAD systems had to frequently print out their ideas.

In the preliminary test, the subject was asked to explain the detailed used to generate their ideas and the trouble they encountered. Their verbal was recorded for future analysed.

The main points recorded included:

1. Ideas

A. The number of ideas;

B. The variety of ideas (5-point scale, 5 for maximum, and 1 for minimum);

C. The effective idea numbers;

D. The percentage of achievement (refer to Appendix C for the design objectives).

2. The design process

A. The statements regarding tool usage;

B. The description of the design process;

C. The description of the thinking process.

The reason why the number of ideas is recorded is that different tools might influence designers in approaching a design problem. The classification of designers' variety of ideas can help the researcher explore the area upon which designers cast their insight. This kind of data will indicate whether designers are heading towards only one or two, or even more directions. It also demonstrates whether or not the tool used in generating ideas can effectively assist designers. On one hand, they might positively help designers in idea development. On the other hand, they might block the designers' creativity. If the designer concludes that his or her idea could be a possible solution to the design problem, it is then considered to be an effective idea. Furthermore, the degree to which the designer's idea matches the design objective will determine the achievement percentage. This can be used to evaluate the alternatives that designers work out for the design problem.

With the subject's verbal narration describing the design process, two categories of data can be analysed and compared: tool usage and process manipulation. To analyse this verbal data, three kinds of statement can be identified: positive, negative, and fuzzy. The "positive data" is defined as those which designers consider helpful to their idea development. If designers' think the tool usage does not help or even creates an obstacle to their idea development, such kind of data will be defined as "negative data". If the verbal statement, in terms of designers' point of view, neither helps nor blocks their idea development, it will be categorised as "fuzzy data."

The statements made by designers are listed below:

Table 4. 2: Designer A: traditional hand drawing and engineering drafting
(1) Statement regarding tool usage

	Positive	Negative	Fuzzy
Hand drawing	It is fast. Designers enjoy the hand strokes; they can do it any time and any place. Like an artist, there are no limits.	Pencils often need to be sharpened. It is hard to control straight lines. The paper is too small. Pencils are apt to break. It is hard to draw ellipses. It is harder to control the proportion. If it is out of proportion, the drawing looks awful and may generate an irregular perspective view.	The kind of pencil and paper plays an important role. The moods will vary in different environments. The hands seem not to work well. Pretty bad in drawing skills.
Eng. drafting	The feeling of drawing is good. The real size can be detected right away.	Wastes a lot of time. Too many tools. The paper is easy to get dirty. It is hard to revise the drawing. It is hard to balance the composition. It is hard to decide the arc. Many repetitions are needed. The paper is folded due to many reasons.	The parallel lines look not parallel. The paper is too big. The compass is not stable. Are these circles tangent or intersection? Is this a square? It looks like a rectangle. This side looks longer (shorter)!

(2) Statement regarding design development process

	Positive	Negative	Fuzzy
Hand drawing	Fast in recording ideas. Designers can do anything they like. Simple pens will do. It makes thinking smoother. There is more continuity between adjacent thoughts. Some ideas are generate accidentally.	We don't know the differences of size. It is not known whether there is enough interior space. Sometimes it is hard to express the product form. It is impossible to draw the forms. It is easy for designers to overlook the performance. Some proportions are not correct. We don't know how it holds.	Sometimes we don't know what's going on. It seems that these ideas are not feasible. Some ideas look good. I like this idea.
Eng. drafting	It is possible to control the proportion. Straight lines and circles are more precise than free hand drawings. It reflects the real size. We can use hands to simulate the operation directly on the drawing.	It is not very clear in some parts of the three side views. It is hard to decide the size of arcs. Hand drawings are still necessary somewhere to help comprehension. If the thought goes wrong, we need to redraw the whole drafting. The tangent arcs are not jointed smoothly. Revision often occurs. The interior space is sufficient from the front view but not enough from the rear side view.	Some curvatures look different from the original thoughts. The original ideas seemed more precise. This idea will not work out right after careful measurement.

Table 4.3: Designer B: computer-aided 2D drawing and 2D engineering drafting

(1) Statement regarding tool usage

	Positive	Negative	Fuzzy
2D graphic software	Colour can be changed at any time. Scaling is easy. It is easy to revise the drawing. Duplication is unlimited. The drawing quality is more delicate. It is convenient to paste pictures and texts. The function of alignment is powerful. The contrast can be adjusted easily. There are a variety of backgrounds.	It is hard to have precise dimensions. Sometimes it is hard to represent the solid effect. The designer should have a strong background of the light and shadow. Some commands are so complicated. Some commands cannot be found. I forget the command's function. There may be sequential limit for some commands. The computer is not fast enough. I forget to save the file. It takes time to have a print out copy. Gradation is not available to some shapes. The format is not correct. It takes time to import or scan a picture.	I couldn't find the file. Where did I save it? The computer is aborted. The file takes too much memory space. When we adjust the higher resolution, the generation speed seems to be slow. The resolution of the monitor is not high enough. The DRAM of the video card is too small. The display speed of computer is getting slow.
2D Eng. drafting	The size is precise. It is easy to distinguish drawings of different colours. Can be revised as many times as possible. Pictures can be duplicated. The array function is great. The rotation function is convenient. The mirror function works well. The interior parts can be built into blocks, and can be rotated or moved.	It is hard to find and judge the intersection line. The solid imagination is required. The views are not precise. Though the size is precise, we cannot simulate the real size of product from the screen. Some lines do not intersect, but naked eyes cannot perceive it. A big arc may be misunderstood as a straight line. It is hard to comprehend the whole product form. It is a trouble to Zoom in and Zoom out. It is hard to judge the internal parts from the three side views.	The original file cannot be found. The resolution is too low. The lines look overlapped. The views may be wrong.

(2) Statement regarding design development process

	Positive	Negative	Fuzzy
2D graphic software	Drawing can be proceeded without entering any parameters. The curves can be changed in a lot of ways. The shape can be adjusted as many times as possible. Curves and lines can be developed from the ready-made objects. Patterns of texture can be easily pasted. It is easy to change the scale.	The dimension is not precise enough. It is hard to define the interior space. There are not enough commands to generate some certain shapes. It takes time to figure out the light and shadow, especially when the effect does not look right.	Ideas are similar. The interior space is not big enough. The colour does not look right. The curvature is protruding.
2D Eng. drafting	Precise dimensions can be entered to the file. Isometric pictures are available. Objects can be duplicated to different files. A revision of the detail can generate a new idea.	It is kind of difficult to draw what is within the designer's mind. Without concrete ideas, it is apt to be constrained to the drawing elements (e.g. Lines, curves,) . If the idea is not satisfactory, it is hard to change it into the form we want. A shape should be carefully considered before starting to work with the computer.	It is not comfortable to hold. Ideas are similar. How does the curvature diminish?

Table 4.4: Designer C: computer-aided 3D drawing

(1) Statement regarding tool usage

	Positive	Negative	Fuzzy
3D drawing	Changes of product form can be precisely represented. The product form can be changed partly from a curvature. Perspective views are precise. The perspective angles can be randomly changed. Different texture patterns are available. Colours can be changed. Several light sources can be set. Solid models can be built from three side views. It features a sense of real world object. The size is precise.	The commands are complicated. There may be sequential limits for commands. Some specific fillets are not available. It is sometimes impossible to change a curvature. The reference plane should be set in advance. Some product form should be built from the intersection of 3D objects. It is hard to predict the intersection line. It takes time to construct such a 3D drawing. It takes time to render.	It is easy for computer to abort. It is sometimes hard to find a command. The file is often huge. The format to transfer is not compatible. The calculation of computer is slow.

(2) Statement regarding design development process

	Positive	Negative	Fuzzy
3D drawing	Ideas can be presented immediately, and the shape features can be verified. Different ways of construction can be applied to the same idea in order to generate different ideas. It is easy to control the internal parts and space.	Product form and the construction ways should be organised in advance. Once an idea is finished, it is hard to revise. The product form cannot be predicted. It is very hard to partly change a component. Some objects should be rebuilt or even the whole product. It is very complicated and time consuming to construct an idea. It is hard to smoothly to construct the shape we want in the first trial.	The curvature of form seems causes an undercut to plastic injection mold. I am not sure that how many centimetres should be given to the distance between the housing and components.

The number of idea records for different designers are listed in Figure 4.3, 4.4 and 4.5. From Figure 4.3, it can be seen that Designer A (free hand drawing) is the highest the number of ideas; Designer B (2D) is second and Designer C (3D) is third. For the effective idea number, Designer B (2D) has the highest and Designer C (3D) the least (Figure 4.3). Though Designer C (3D) is lowest in the idea number, the percentage of effective ideas in relation to total ideas is 60%, the best in three design groups (Figure 4.4).

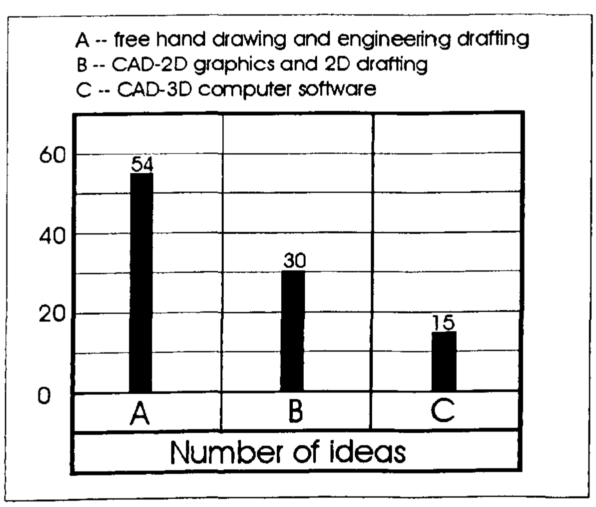

Figure 4.3: The number of ideas for 3 designers

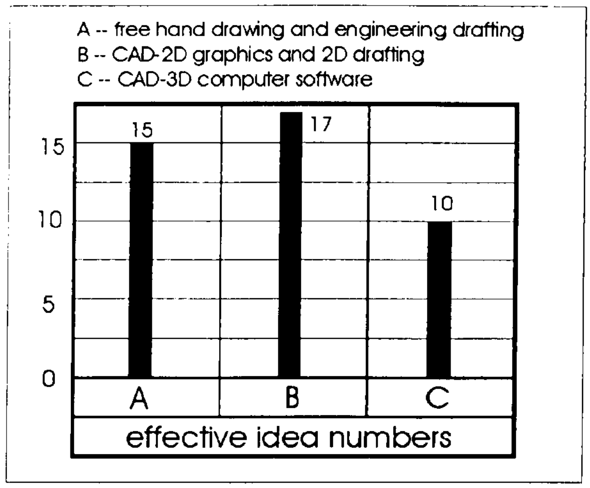

Figure 4.4: The effective idea numbers for 3 designers

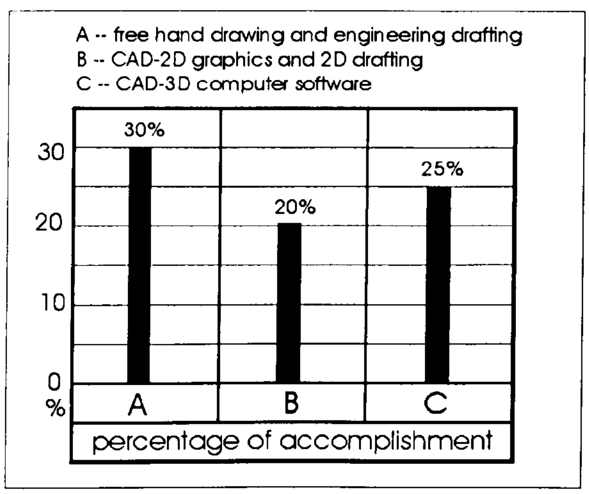

Figure 4.5: The percentage of accomplishment for 3 designers

4.4 Analysing the Statements of Subjects

Analysis of the statements of Designer A

The description of tool usage by Designer A is common to most designers. According to the statements made it is clear that speed, simplicity, no limitation of space and time are the advantages of free hand drawing. Additionally, Figure 4.3 shows that Designer A produced the biggest number of ideas (54), which means that it allows designers to generate a lot ideas. However, the designer's characteristics are also an important factor. Some designers tend to challenge the difficult problems with active attitude, other designers doesn't.

Such a corresponding relationship lays a foundation for a framework of tool usage and idea generation. However, there are only 15 ideas (see Figure 4.4) considered by the designer A himself to be close to the design objective, accounting by 30% of the total ideas (see Figure 4.5). The high percentage (70%) of ideas that did not reach the design objective was due to problem with the tool usage (e.g., not easy to control the proportion, size not precise in sketches). Its degree of precision is very low so designers need to spend lots of time revising and interpreting the drawing. The uncertainty of ideas is really a primary factor in the early stage of idea development. Take Figure 4.6 for instance, designers rejected it because its internal space was not sufficient and as there might be problems in hand holding. The difficulty lies in the complicated curvature. We do not know if the internal components can fit it well. In addition, the concave curve in location A was not satisfactory to the designers even though it had been revised many times. To make the matter worse, the designers did not favour its basic form. The hand drawing, therefore, did not therefore achieve the design objective.

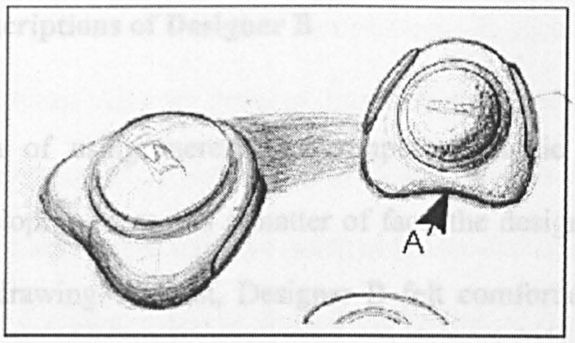

Figure 4. 6: A sketch of driving assistant device of designer A.

When it is necessary to transfer the hand drawing to the engineering drafting, designers need to switch from one mode to another or vice versa frequently. If the geometric engineering drafting is not suitable for evaluation, the hand drawing sketches will then be adopted. Indeed, a lot of information about the solid pattern is hidden from the three side views of engineering drafting. The switching back and forth from hand drawing to engineering drafting, therefore, is common and inevitable. The application mode of hand drawing is shown in Figure 4.7, which resembles a cyclic pattern. Meanwhile, the engineering drafting will also help designers to keep moving forward.

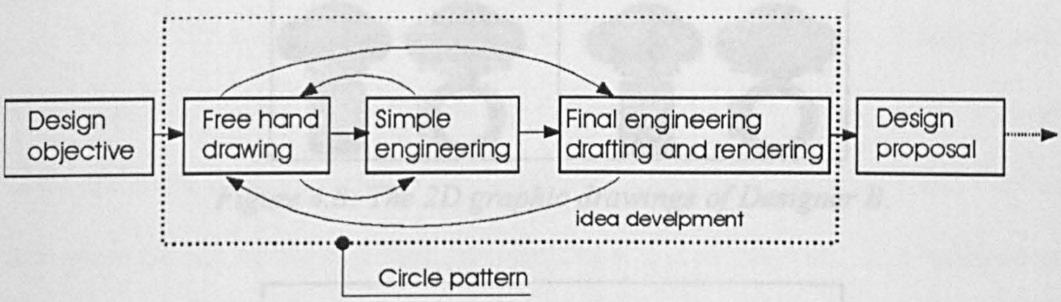

Figure 4.7: The application mode for designer using free hand drawing and drafting

Analysis of the descriptions of Designer B

The limitation of using merely 2D computer graphic software did frustrate Designer B in developing ideas. As a matter of fact, the designer was not good at the skill of free hand drawing. At first, Designer B felt comfortable in generating ideas using 2D software. However, with the increase in the complexity of design problem, it was difficult for him to explore the design problem through 2D software only. Moreover, it depended a lot whether the designer is equipped with proficient skills in drawing colour and solid shape (see Figure 4.8). 2D graphic software is not good in terms of precision. Designer B drew directly on the screen and it was therefore, very hard to evaluate the actual physical size of the idea. Another problem arose when the designer needed to make decisions on adjusting the brightness and hue for shadow effect, which would affect the nature of the final product form.

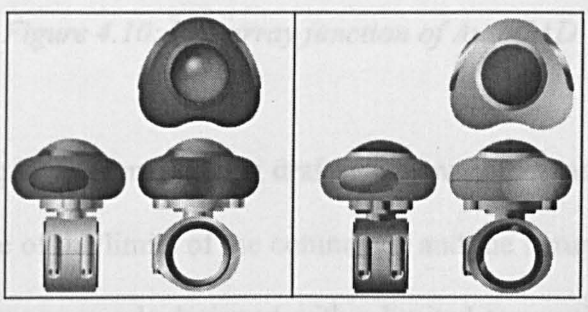

Figure 4.8: The 2D graphic drawings of Designer B.

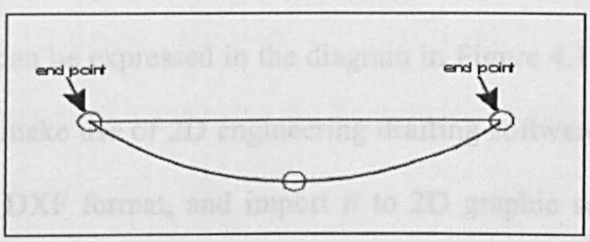

Figure 4.9: The curve editing in AutoCAD

To obtain better precision in terms of proportion, Designer B used 2D engineering drafting software (AutoCAD) to develop ideas. Single geometric elements (circle, rectangle, ellipse, polygon, etc.) were often used as basis for idea generation. He also tried to use curves to search for different product forms. Because it's not easy to define curves, and because it's impossible to change the angles of the end points at the same time, Designer B was heavily constrained in evaluating product form (see Figure 4.9). In AutoCAD, on the contrary, the command of duplication saved Designer B lots of time, and so did the command of Array (see Figure 4.10).

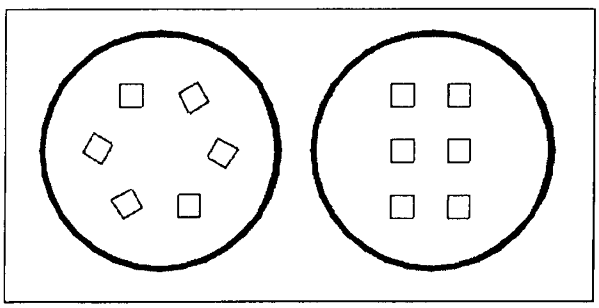

Figure 4.10: The array function of AutoCAD

Neither 2D graphic nor engineering drafting software can meet all the requirements of designers because of the limits of the commands and the nature of the software. Still there are some other commands designed with a limited sequential order. For example, designers cannot revise a picture in CorelDraw if it is grouped. The application mode for such designers can be expressed in the diagram in Figure 4.11. Finally, another way for the designer to make use of 2D engineering drafting software is to transfer the side views into files of DXF format, and import it to 2D graphic software for colour and texture processing.

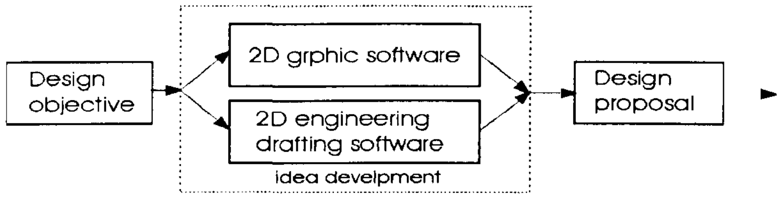

Figure 4.11: The application mode for designers using 2D graphic or engineering drafting software

Analysis of the descriptions of Designer C

There are many more difficulties in constructing 3D drawings. In particular, a lot of designers were awe-stricken by merely looking at such software owing to the complicated commands. And there are some commands whose functions are designed require a specific sequential order. To revise a model built by such commands, designers need to follow a special construction. Besides, it is sometimes difficult to proceed the Fillet function in certain 3D forms. For example, an intersection line will be formed when a model is intersected with another one. If the intersection line is processed the Fillet command, it will be impossible to apply the Fillet command to the new intersection line formed by another model and these two models. Similar problems will occur in constructing 3D models. If the intersected models are of irregular shapes, then it is much more difficult for 3D drawing software to deal with the intersection line. In fact, to construct a 3D model, designers will first build 2D models in MicroStation. Hence, the basic concepts of engineering drafting are also indispensable to designers.

During idea development process, designers should have concrete ideas and understand to a certain degree how to construct models. Designer C had encountered some problems. If the designer wanted to modify a model already constructed, there are only a few options due to the available construction methods. For example, Designer C intended to transform model A as shown in Figure 4.12 into another one with an attractive form. He chose the command Extend to stretch the circle to an ellipse (see model B in Figure 4.13). Again he used model A to make a bigger alternation by applying the command Cutting and got the form of model C (see model C in Figure 4.14).

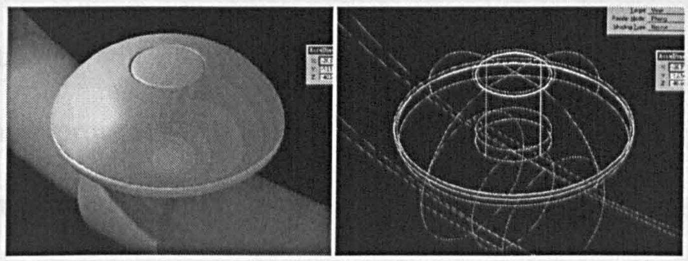

Figure 4. 12: The model A of Designer C

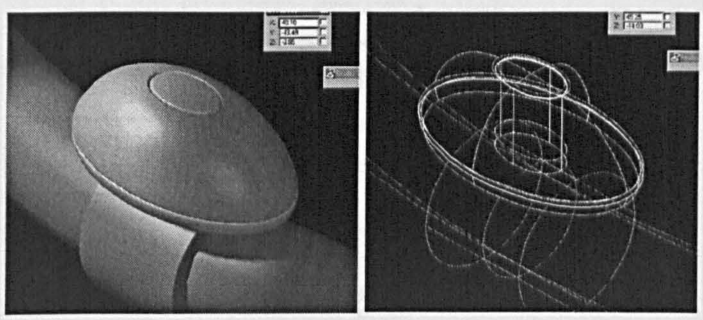

Figure 4.13: The model B of Designer C

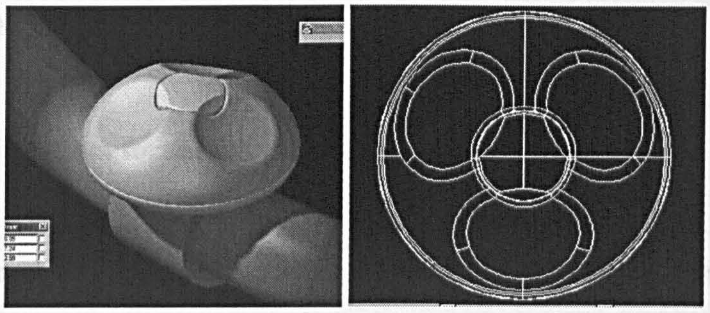

Figure 4.14: The model C of Designer C

From this case, we can see that designers are constrained by the commands in thinking how to improve the product form. When a basic model is finished, they tend to choose some of the available tools that make it easy to predict the new form. Such technical limitations will of course hinder designers' imagination and creativity. The idea development process for this kind of 3D tool is shown in Figure 4.15. From the diagram, the inner thinking plays an important role. Their thinking should consider both the patterns of form and methods of construction (2D and 3D).

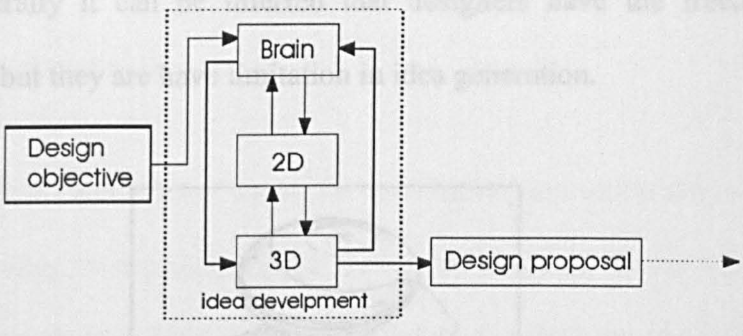

Figure 4.15: The application mode of Designer C

4.5 Synthesises and analysis of findings

- **Analysis of product form characteristics**

In free hand drawing mode, designers also used drawing tools such as triangle, French curve, circular or elliptical templates to support their idea development. Figure 4.16 shows an example where circular and elliptical templates are employed and Figure 4.17 is an example in which French curve and streamline templates are used to develop ideas. Comparing the free hand sketch in Figure 4.18, we can understand that the characteristics of various forms are greatly influenced and limited by the tools. The sketches in Fig. 4.18 are full of freedom and uncertainty, which allow a lot of room of the imagination of the designers. For the sketches in Figure 4.16, and Figure 4.17, they are much more precise, but limit the imagination. A careful examination of the 2D graphic and drafting ideas shows that they are similar to models constructed in 3D software. Generally it can be inferred that designers have the freedom to choose computer tools but they are have limitation in idea generation.

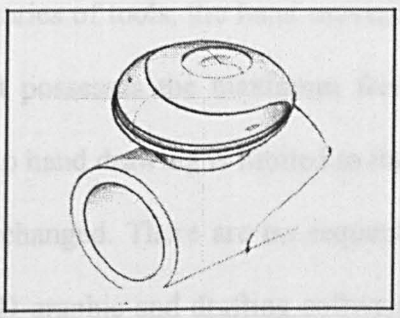

Figure 4.16: The sketch 1 of Designer A

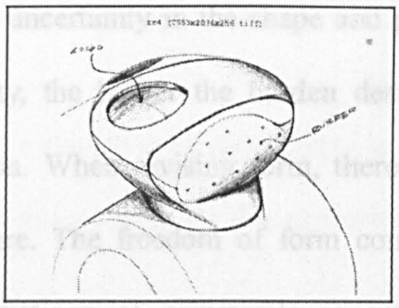

Figure 4.17: The sketch 2 of Designer A

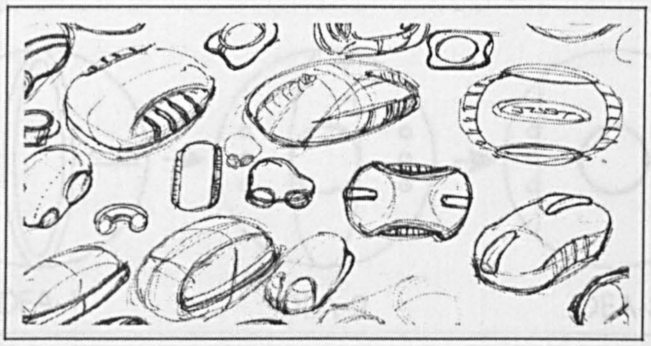

Figure 4.18: The free hand sketch of Designer A

- **Comparison of tool usage**

Among these three categories of tools, the hand movement or the nerve centre controls hand free drawing, so it possesses the maximum freedom, but is least precise. The application of templates to hand drawing is limited to their shape and curve, but they are flexible and can be interchanged. There are no sequential limitations or difficulties in construction. As far as 2D graphic and drafting software is concerned, they are limited to the primitive elements. More complicated forms should be composed step by step and are constrained by the commands and programming structure. In the application of commands, 2D software is much easier than 3D software. The ideas constructed in 3D are extremely limited by uncertainty in the shape and proportion. During construction the bigger the uncertainty, the bigger the burden designers have to shoulder in re-thinking and manipulation. When revising form, there are more limitations with 3D software than 2D software. The freedom of form composition is constrained to the sequential order and functions of commands as well as the methods of model construction.

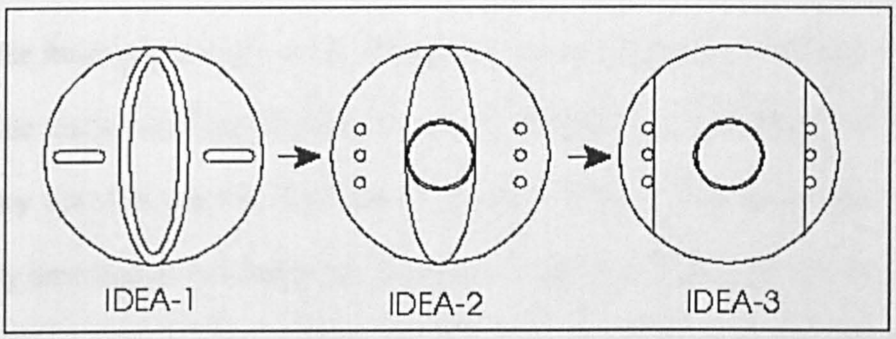

Figure 4.19: From idea 1 to idea 3 Designer B just used the Array, Copy and Mirror commands to create ideas with AutoCAD.

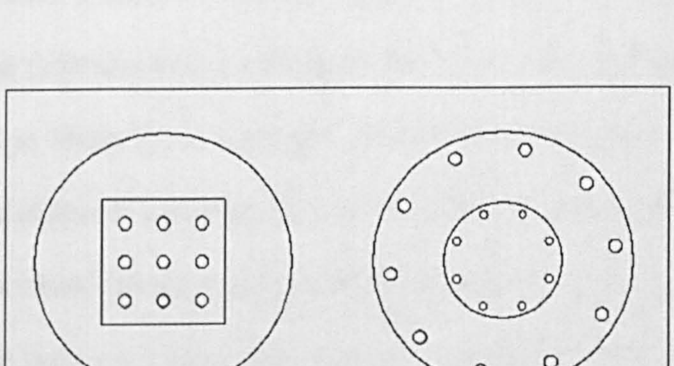

Figure 4.20: Using "Array" command to create ideas with AutoCAD

• **Analysis of the design development process**

Many researchers have studies the issues related to free hand drawing and drafting. In this study, the author is interested in the design development processes in 2D and 3D drawing software.

(1) The application of 2D drawing and 3D drafting software in idea development

With the functions of copy, array, rotate, and mirror, 2D graphic software is different from the traditional hand drawing. In terms of copy, the same object can be copied as many times as possible and may be partly revised. At the same time, it can be linearly arranged or overlapped to develop the optimal form designers are alter (see Fig. 4.19). For the command Array, an object can be placed vertically or horizontally at some distance to form a matrix or rotated to different angular arrangements (see Fig. 4.20). Such a function enables designers to explore various matrix arrangements for a certain form element in a short period of time. The interval of distance can also be adjusted to obtain better compositions. The third command is Rotate. It can move an object in different angles so that the designer can observe the feeling of the shape at different levels. There is a big difference between symmetric and asymmetrical forms when they are rotated. Similarly, the command Mirror can achieve the same result as the command Rotate. It enables designers to see an asymmetrical object in the opposite side. Designers can choose left-right or up-down mirror function. These functions are rarely seen in traditional way of hand drawing unless a transparent paper is used.

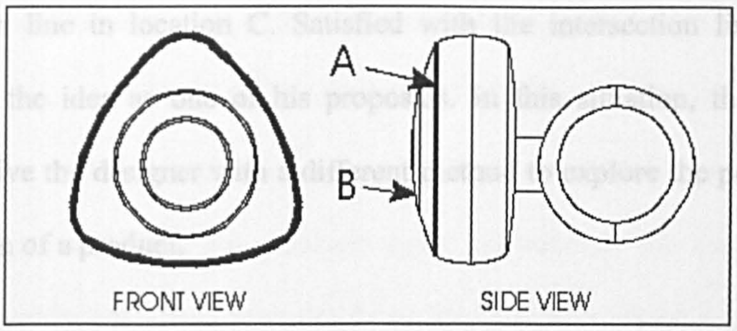

Figure 4.21: The orthographic drawing of Designer C's image of mind

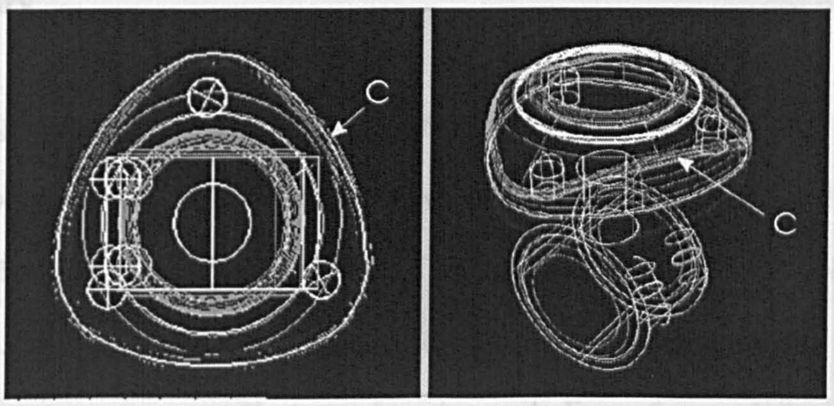

Figure 4.22: The wire frame of 3D model in computer with Microstation

(2) The application of 3D drawing software in idea development

During the idea development process, designers have in their minds some concepts of product form as can be seen in Fig. 4.21. The drawing illustrates designer C's ideas for the design project. However, it is not easy to construct the straight line in location A or the spherical plane B. The front view of Fig. 4.22 is the basic form. With the triangular curvature and protruding spherical curvature, it is not easy to compose the line in the software. Consequently, the designer directly put the spherical and the triangular curvatures together and there came accidentally an intersection line in location C. Satisfied with the intersection line, the designer handed in the idea as one of his proposals. In this situation, the 3D modelling software give the designer with a different method to explore the possible solutions for the form of a product.

4.6 Summary

Aggregating the analysis mentioned above, we know that the choice of tools for idea development and the characteristics of these tools will remarkably influence designers' thinking. No matter what kind of tool designers choose, the tool will partly affect them. Moreover, the characteristics of the tool, like as templates or software commands and structure, will determine the underlines form of the constructed compositions or models; the forms constructed by designers will exhibit the nature of the graphic tool. Like a person's handwriting, every character is different, but there will be a high homogeneity. It will occur even in drawings. That is to say, if different people choose the same tool, under some certain constraints (e.g., design direction or objective), they are likely to obtain a form where characteristics are similar. In free hand drawing, however, the probability is much lower.

Besides, there are some difficulties in idea development, which cannot be overcome right now using either a 2D or 3D drawing software. However, these drawing software tools provide designers with other ways to explore the product form. For example, the model construction of the commands of Copy, Rotate, Array, and Mirror in 2D graphic software as well as the manipulation of the intersection line in 3D software are not possible with the traditional approach. It seems that designers have enjoyed these new functions. From the analysis early mentioned, the execution of such commands, nevertheless, often provides hints for designers about a new direction of product form. In a way, they educate the designers. Designers get opportunities to explore and learn from 2D and 3D tools. On the other hand, they also expand the scope of designer's mind and imagination.

The computer software discussed in the paper is not the most powerful or representative. They may not represent the characteristics of other CAD systems. More important, these kinds of computer software package were not designed for idea development, but for the visualisation of product design (Elas and Vergeest, 1998). There are still many things that need to be explored. In practice, designers apply 2D and 3D software in different stages due to their characteristics and functions. The multiple modes in applying CAD systems for idea development are an important field of research. While exploring the design development from idea generation and design refinement, the researcher arranged the advance study in terms of 3D-model construction in idea refinement stage. The next study is described in Chapter 5.

Chapter 5 Exploring designers' 3D-modelling processes in a CAID environment through verbal protocol analysis

5.1 Introduction

In the previous chapter, an examination of the idea generation stage was conducted to explore how the different tools used influence the designer performing design tasks. The 3D modelling tool is not suitable to use in the idea generation stage, but it is important in the final refinement stage of idea development, and the phase of the designer turning his 2D graphic ideas into 3D form. In this phase industrial designer need to apply form detail, precise dimension, surface texture, colour, and consider moulding techniques and manufacturing using their 3D-software package. To understand designer's thinking and behaviour, the researcher decided to conduct an investigation of this design stage. This understanding will then enable the researcher to find key factors for a new CAID system.

In this chapter, verbal protocol analysis was used to explore the industrial designer's use of 3D modelling in a CAID system. Emphasis was placed upon how designers use CAID software to achieve their design goals. During this process, the way designers think about various requirements related to the problem and how to manipulate the idea refinement of 3D modelling are involved.

To understand the designer's thinking process, the verbal protocol framework described in Section 2.4 (please refer to Figure 2.29) was employed to analyse the designer's mental processes. In this study, different designers and design episodes were investigated to record the design behaviour by getting them to think aloud.

Dictation and video recording were then used to record the contents and design behaviours based upon the problem domains and design strategies (These two categories were discussed in the following sections.). The distribution patterns of the properties on the criteria of timing were analysed and discussed. According to the CAID survey made in Chapter 3, in order for the designers to perform the refinement task in they need to conduct model construction and consider design factors relate to their ideas. So, Design Development (refinement) and 3D-Model Construction are involved in design refinement stage when CAID systems are used. These two types of design activities are the major concerns of this analysis section.

5.2 Verbal protocol analysis

The verbal protocol analysis the researcher conducted in this chapter is based upon the framework proposed by Gero and Mc Neill (1998). The key point of the verbal protocol analysis is the coding scheme, which is also the most important basis for further analysis. As mentioned earlier, the verbal protocol is made up of many segments of the protocol scheme. The content and activity of the design episodes often decide the coding scheme. Design episodes, therefore, should be defined and discussed according to the characteristics of the research objectives of which this study is one.

According to the content of Figure 2.29, it is clear that coding schemes should follow the definition of problem domains and design strategies so as to conduct the coding task. The definitions of the problem domains and design strategies vary with the different design episodes. Consequently, the researcher should take the characteristics of this research and industrial design activity to properly set their definitions. This will be discussed in the following section.

Segments are made according to the subject's verbal protocol and can be considered as the representation of the designer's attention and behaviour patterns. The results of the coding of the segments, therefore, can be changed into a diagram where the distribution of the designer's strategies and the frequency of design activities can be illustrated along the axis of time. From these diagrams, the characteristics of the designer's activities can be explored.

5.2.1 Designer's verbal and behaviour recording

To observe and record the designer's behaviour and narration, two video cameras were used to take down the visual images and audio data, one for the graphics on the screen, and the other for the environment around the subject. The data and graphics on the screen served as the basis for coding, while the computer, monitor, office furniture, other peripherals and the subject (Figure 5.1) offer some other data for verbal protocol analysis. In addition to the interaction between the designer and the computer, other design activities are also recorded. Based upon the graphics on the monitor and the designer's behaviour, more reliable coding can be made. More importantly, some behaviour and mental processes that are not verbally presented can be extracted from the video recordings.

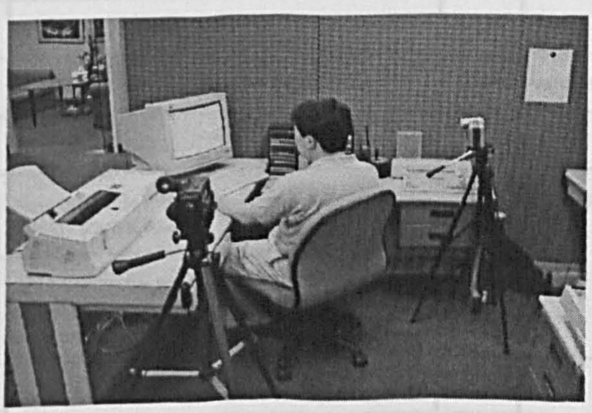

Figure 5.1: The video recording situation of the protocol experiment

During the video recording, the designer can stop the design activity or take a break because it might take one or two hours or even a couple of days to finish a design task. In these cases, the video camera will be shut down or put on stand by. Besides the video data, the sketches or texts the designer uses to communicate with the CAID operator or other designer are also included.

To conduct the coding task, the raw data of the verbal protocol experiment (Table 5.1) was taken down from the video recordings. The encoder will then turn them into a series of effective segments according to the coding method.

Table 5.1: A fragment of raw protocol for design episode A

No	Design Development	Model construction	Dialogue	Timing	Action
1			I will do the contour profile of the top view.	0.22	Draw a circle and adjust the scale
2			Draw according to the standard dimension.	1.28	Discuss it by the rendering
3			But I don't know how to set the precise dimension now.	1.31	
4			So, you don't need to care about the precise dimension now.	1.36	
5			Just the rough shape!	1.40	
6			Rough. Then this is probably not covered.	1.42	
7			So it reads 54 and 47.	1.46	Pick object
8			It should work!	1.53	Set command parameter, delete the circle
9			Wrong.	2.26	Draw a circle
10			Pick object. I will enlarge the view.	2.34	Adjust the scale
11			Something weird.	2.45	Del the circle
12			Now the circle means the dimension or you have already started building the body.	3.06	Discuss with others
13			Oh, I just try the rough shape. My teacher had taught us how to adjust the correct dimensions. But I am not familiar with it.	3.11	
14			Ok, go ahead.	3.19	

5.2.2 Design episodes

Design episodes in this study cover four product designs: Back Cushion Massager, Talking Clock, Night-Light, and Power Adapter. The design objectives of these design episodes can be seen in Appendixes D, E, F, and G. These four design projects are different in form and their inner functions. The Back Cushion Massager is made of plastic fabric, which is considered to be easy for thermal forming to achieve a high quality surface. The Talking Clock works through digital processes to generate the voices and alarms and is contained by plastic housing. The Night-Light is used with an outlet through an electronic process to generate light. The Power Adapter is used in a car to provide the electricity for PDAs or portable CD players with 24-selections for power output in voltages.

The researcher chose these design episodes because of the following four considerations: (1) they should be mass-produced in the near future. If they were only assumptive episodes, the subject would not consider the problems for production and usage in a serious manner. This would affect the reliability of the observation. (2) There should be some differences in terms of the product form. If they have similar product forms, the construction procedure and problems they will encounter during Design Development and 3D modelling will be similar (Please refer to the summary section of Chapter 4). Such a consideration is indispensable for further differential contrast and comparison. (3) Different designers and computer operators that work for different design groups should be chosen to execute different design episodes. Designers and computer operators chosen for the verbal protocol test should have different characteristics in terms of design experience; for example, the work experience, professional discipline (mechanical engineering or graphic design), industrial designers or computer operators, users of different 3D software, and so on.

For these four design episodes, the CAID stage that comes after the idea generation stage was focused on. The researcher, therefore, knew the initial product form and the 3D software the subjects were going to use before video shooting. In some design episodes, the product form construction subjects include only one designer and in other cases, a computer operator accompanied the designer. Because different manners of designing are undertaken in different design groups, the choice of different subjects will make it possible for the author to compare the influences professional background has on CAID application. In this study, therefore, a designer and a computer operator were chosen in two design episodes and only a designer was selected to proceed the design project in other two design episodes (Table 5.2). As for the product forms of these four design episodes, please refer to the 2D renderings that were created in the initial idea refinement stage from Figure5.2 to Figure5.5.

According to the CAID system survey in Chapter 3, four kinds of the most popular software, Pro-Engineer, Alias, Rhinoceros and Ideas, were selected (Figure 3.19). From the result of the survey in Chapter 3, it is known that 3D modelling is a stage for refining the rough product form so as to improve the design quality (See 3.5 summary, pp. 120~123). This is the reason why the researcher decided to observe and record the 3D modelling stage of the idea refinement procedure. It would take too much time if all the design activities were to be observed and recorded. In addition, it would blur the focus of the study. The huge amount of data would also go far beyond the scope of this research.

Table 5.2: The distribution of the subjects and design episodes

Design Episode		Subjects	Experiences	Software	Places
A	E.L. Night Light	One Industrial Designer	1 year on ID Half year on Alias	Alias	Neway Design
B	Back cushion Massager	One Industrial Designer	12 years on ID	Pro-E	Fine Corporation
		One Computer Operator	5 years on Pro-E		
C	Talking Clock	One Industrial Designer	10 years on ID 3 years on Ideas	IDEAS	AND Design
D	Power Adapter	One Industrial Designer	15 years on ID	Rhino	Leader Electronics INC
		One Computer Operator	1 year on Rhino		

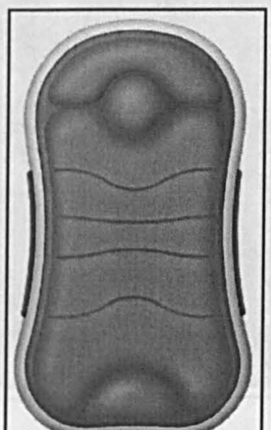

Figure5.2: The 2D drawing of the back cushion massager

Figure5.3: The 2D drawing of the talking clock

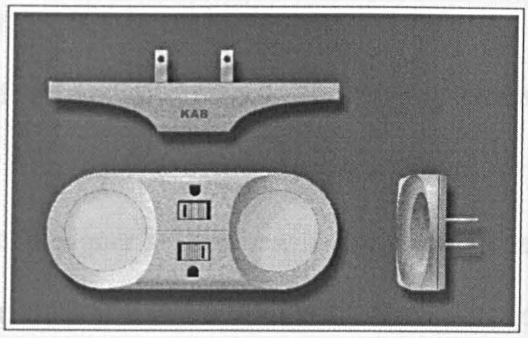

Figure5.4: The 2D drawing of the EL night-light

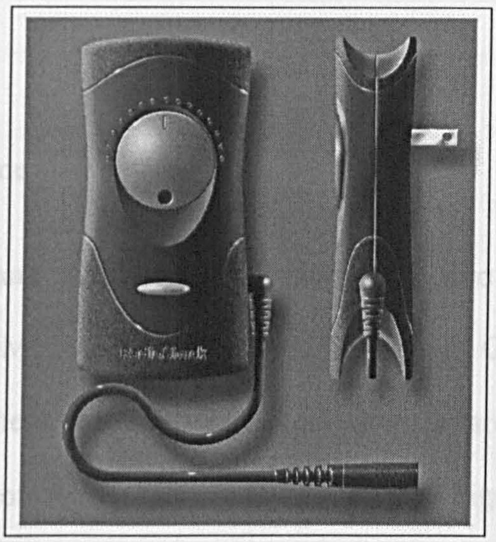

Figure5.5: The 2D drawing of the power adapter

5.2.3 Segmentation

A segment in this field research's terminology corresponds closely to an episode in the terminology of van Someren et al. (1994). The transformation of designer's or computer operator's attention in the verbal protocol can be looked upon as the start of a new segment. Table 5.1 illustrates some segments of the verbal protocol. In the table, the first column is the order number of the segments, the sequence of the segments. The second and third columns represent the Design Development and Model Construction respectively. They are coded based upon the subject's protocol in terms of the category, to which subject's attention belongs. The Dialogue column records the content of the verbal protocol. The Timing column records the starting time of the subject's action. The Action column describes the subject's detailed actions, including the designer's sketches, asking questions of others, retrieving related information, or the status of the Model Construction during the segment. The purpose of this column is to help the encoder precisely identify the actual design action so as to build a more reliable protocol database.

5.2.4 Coding scheme

The coding scheme divides the segments into two coding parts: Design Development and 3D Model Construction. In the use of CAID, according to the survey in Chapter 3, these two kinds of design activities are involved. The coding task, therefore, is in accordance with these two categories (Figure5.6).

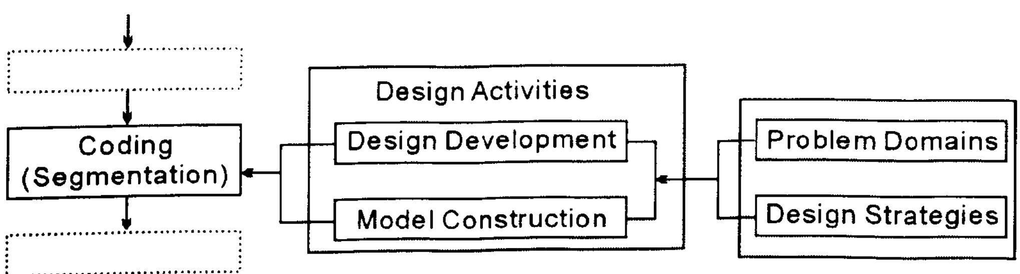

Figure 5.6: The flow chart of the coding scheme and design activity

Coding was also made according to the contents of problem domains and design strategies. The definition and boundary of problem domains and design strategies, therefore, will greatly influence the results of coding. Their definitions will be delineated in the following section.

5.2.5 Problem domain

In Table 5.3, the second column (PD) is used to describe the problem categories and boundary in a certain design episode. For the sake of consistency and convenience in coding tasks, the category of problem domains was used. All the problem domains fit the contents and properties of the four design episodes.

As mentioned in section 5.1, it is known that the process of a design episode will involve Design Development and Model Construction. The contents of these two activities, however, are totally different. On one hand, design development involves the evaluation and deployment of the design problem. In these kinds of activities, industrial designers need to take all design issues into consideration. Please refer to Table 5.4 for the professional knowledge and problems for the industrial design problem domain and the initials of their categories.

Table 5.3: A fragment of final protocol in design development for design episode A

Time	PD	MI	Ma	Dialogue	Actions
0.22	Sh	Ps	Td	I will do the contour profile of the top view.	Draw a circle and adjust the scale
1.28	Sd	Cl	Td	Draw e1 according tot he standard dimension.	Discuss it by the rendering
1.36	Sd	Pp	Td	So, you don't need to care about the precise dimension now.	
1.40	Sd	Dd	Td	Just the rough shape!	
1.42	Sd	Dd	Td	Rough. Then this is probably not covered.	
1.46	Sd	Ca	Td	So it reads 54 and 47.	Pick object
1.53	Sd	Dd	Td	It should work!	Set command parameter, delete the circle

Table 5.4: The categories of problem domains for the design development task

Category	Problem domain
Outwards Physical Element	Dimension (Sd)
	Form (F)
	Colour (C)
	Texture (T)
	Material (M)
	Weight (W)
	Shape (Sh)
Graphic	Symbols (Sm)
	Characters (Ch)
	Letter Type (Lt)
Technology	Manufacture Method (Mm)
	Moulding (Mo)
	Assembly (A)
	Surface Treatment (St)
	Function (Fu)
User	Using (U)
	Interface (I)
	Human Factor (Hf)
	User Group (Ug)
	Psychology (Ps)
Product Structure	Housing (H)
	Parting Line (Pl)
	Strength (Sr)
	Parts (Pa)
Economic	(E)
Culture	(Cu)

On the other hand, Model Construction refers to the computation task designers employ for 3D visualisation. The problem domains of this activity are different from those of Design Development. They are much more related to the form factors designers need to consider in constructing models. In this study, points, lines, and planes were used as the primitive criteria for classification of the construction actions. Please refer to Table 5.5 for the contents of the composition elements. Among them, the edge belongs to the line family. In the study, it is special and represents the line formed when two surfaces intersect with each other. From the product form proposal made by designer C in the discussion section of Chapter 4, we know that it is sometimes more difficult for designers to predict and control the change of intersections. To explore the difficulties designers might encounter in constructing models, this kind of line (edge) was included in the category of form elements.

Table 5.5: The categories of problem domains for the model construction task

Point	Position (Pp)
	Dimension (Pd)
Surface	Position (Sp)
	Dimension (Sd)
	Curvature (Sc)
Line	Position (Lp)
	Dimension (Ld)
	Curvature (Lc)
	Shape (Ls)
Edge	E
Form	F
Plane	P

5.2.6 Micro Strategies

The design strategies designers may apply in the design procedure can be categorised into two groups: Micro Strategies and Macro Strategies (see the third column and the fourth column in Table 5.3).

Micro Strategies, again, can be categorised into three groups: analysing a solution; proposing a solution and making explicit references (Pahl and Beitz, 1984; French, 1985; Coyne et al., 1990; Gero and Mc Neill, 1998). Table 5.6 lists the corresponding conditions of the categories and protocol in these three groups. According to the definition made by Gero and Mc Neill (1998), the categories for

Micro Strategies can be described as follows.

Table 5.6: The Micro Strategies used in the four design episodes (Source: Gero and Mc Neill, 1998)

Micro Strategy Category	
Proposing Solution	
Ps — Proposing a Solution	• The way to Solve that is...
Cl — Clarifying a Solution	• I'll do that a bit neater...
Re — Retracting a Previous Solution	• That approach is no good what if I...
Dd — Making a Design Decision	• OK. We'll go for that one...
Co — Consulting External Information	• What are my options...
Pp — Postponing a Design Action	• I need to do ...later
La — Looking Ahead	• These things will be trivial to do.
Lb — Looking Back	• Can I Improve this solution?
Analysing Solution	
An — Analysing a Proposed Solution	• That will work like this...
Ju — Justifying a Proposed Solution	• This is the way to go because....
Ca — Calculating on a Proposed Solution	• As above but using calculator.
Pa — Postponing an Analysis of Action	• I'll need to do work that out later
Ev — Evaluating a Proposed Solution	• This is faster, cheaper etc...
Explicit Strategies	
Ka — Referring to Application Knowledge	• In this environment it will need to be...
Kd — Referring to Domain Knowledge	• I know that these components are...
Ds — Referring to Design Strategy	• I'm doing this the hard way...

Proposing a Solution (Ps) means that the designer proposes a solution (he or she considers being a solution) to the design problem. Clarifying a Solution (Cl) means that the designer carefully considers or defines the solution he or she proposes. Retracting a Previous Solution (Re) means that the designer decides to give up a solution after revising and struggling. Making a Design Decision (Dd) means that the designer decides to execute a design solution after prudent evaluation.

There are five other categories related to the behaviour of analysing the solution. Analysing a Proposed Solution (An) means the quantitative or qualitative analytic behaviour the designer uses towards the solution. Justifying a Proposed Solution (Ju) means that the designer examines or assesses the proposed solution. Evaluating a Proposed Solution (Ev) means the behaviour the designer uses to make an evaluation qualitatively about the proposed solution.

Consulting External Information (Co) indicates that the designer is looking for other information for the reference of solution so as to determine the nature of the design problem and the design direction. For example, the designer may need to look for texts and pictures about the design problem. Postponing a Design Action (Pp) means that when the designer is concentrating himself or herself on a solution, he or she finds it is necessary to stop the process towards a solution because he or she needs to consider some other factors. Looking Ahead (La) means that, after making a judgement, the designer decides that the current design direction is not important and starts a new one. Looking Back (Lb) represents changed behaviour the designer proposes for the solution previously made.

The last three categories represent the specific knowledge or domains the designer refers to. Application Knowledge (Ka) means the application technology or other factors to be considered about the design solution. Domain knowledge (Kd) represents the professional knowledge the designer quotes or refers to. Design strategy (Ds) means the status that the designers evaluate the design schedule or evaluate of the design strategy he or she is proposing.

5.2.7 Macro Strategies

The definition of the Macro Strategies refers to the properties of cognitive models. There are five categories of Macro Strategies: Top Down, Bottom Up, Decomposing the problem, Backtracking, and Opportunistic. The category of Macro Strategies is decided by a series of segments and their contents. Among them, Top down (Td) means that the designer chooses to deal with the problem of a higher hierarchy first and then that of the lower hierarchy. Bottom Up (Bu), on the contrary, means that the designer chooses to deal with the problem of a lower hierarchy first and then that of a higher hierarchy. Decomposing the problem (De) refers to the process where the designer decomposes the design objective or the total design problem into some easy-to-identify or easy-to-comprehend parts. The period of time for Backtracking (Bt) and Opportunistic (Op) strategies is shorter than those of the strategies mentioned above. Thesc two strategies happen only when the designer feels that the design needs to be refined or there is something not quite right. Backtracking (Bt) refers to the status when the designer feels that the Design Development does not reach the expected result and does not know how to go further. In this case, the designer will trace back the solutions previously tried and may make some attempts to revise tasks. Opportunistic (Op) means that the designer changes his or her Macro Strategy after considering varying factors.

5.3 Coding process and method

According to the research flow chart mentioned in Chapter 2 (Figure 2.29) and the conclusion that Design Development and Model Construction should be covered in the coding, the more detailed coding framework is shown in Figure 5.7. The content reflects that the actual coding is the time and energy consuming stage of the study.

During the coding process, the Design Development and Model Construction were made based upon the same design strategies. The problem domain is different. Please refer to Section 5.2.5 for the detailed content of the problem domain. Two results for these two design activities, therefore, will be obtained. They will be contrasted and compared to explore the characteristics of design activities in the

CAID environment.

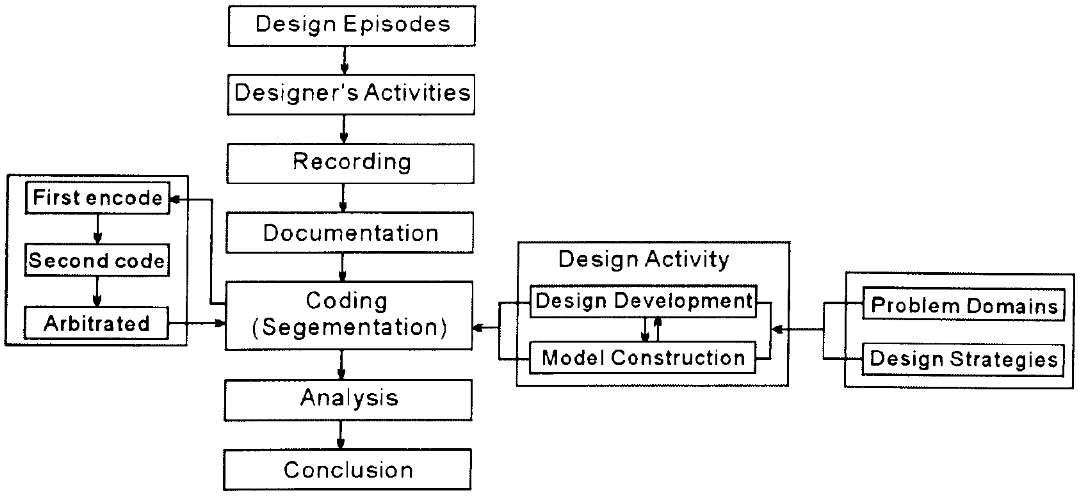

Figure 5.7: The flow chart of verbal protocol analysis and its coding process and method

5.3.1 Coding method

There are two stages for the researcher to complete for the verbal protocol method. The first stage adopts some methods to describe and record the design procedure in an objective manner, which is similar to the Delphi Method. The second stage transforms the output of the designer's design procedure into a visual diagram for further analysis and comparison.

The Delphi Method is a technique developed by Linstone and Turoff (1975). They defined it as follows:

"Delphi may be characterised as a method for structuring a group communication process so that the process is effective in allowing a group of individuals, as a whole, to deal with a complex problem."

Gero and Mc Neill (1998) pointed out that the Delphi Method consists of four phases.

(1) In the first phase, the research team and experts investigate the property of the problem and search for related information, trying to look for a proper way to identify the research issues.

(2) The team members should then be able to understand the problem to a certain degree.

(3) When the members have significantly different viewpoints about the problem, the reason should be explored and evaluated.

(4) Conduct the final evaluation of the results and judgements previously obtained.

In this study, the author is the only encoder. These four phases were followed for the coding task. The coding procedure is shown in Figure5.8 and Table 5.7.

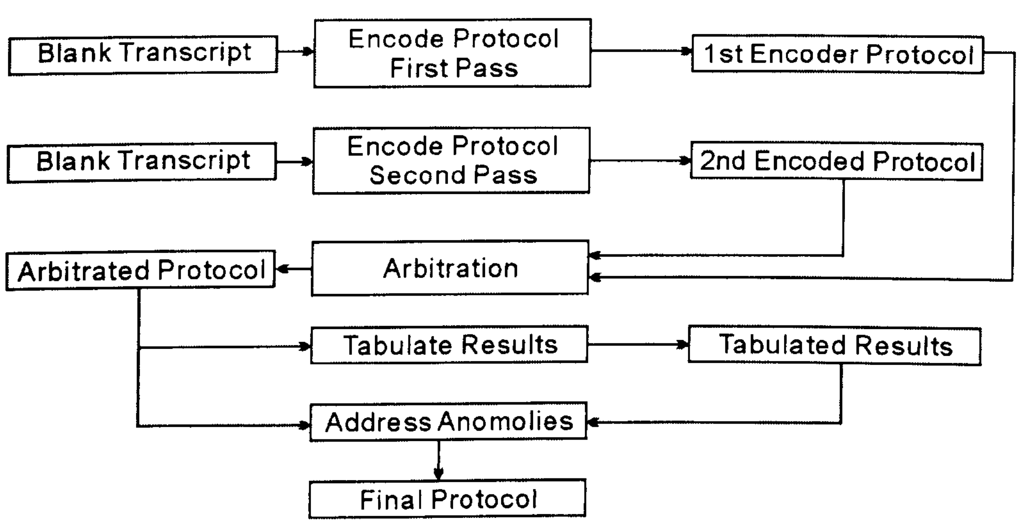

Figure 5.8: The coding method (Source: Gero and Mc Neill, 1998)

For the protocol data of design episodes, there will be two encoding cycles. In addition to the detailed checking of the comments made and sketches, some ambiguous verbal data was defined by reference to the video recordings.

Coding was taken down according to the problem domains and strategies. To obtain more reliable protocol data and objectivity, there was an interval of about ten days between two coding tasks. By doing this, the current coding would not be affected by any previous experience or biased impression.

When the second coding was done, it was compared with the first one about ten days later. Finally, the protocol data was completed.

5.3.2 Coding Consistency

When the first and second coding tasks are finished, the researcher needs to confirm whether they are consistent or not. If there are inconsistencies, the researcher needs to make a decision through the arbitration the coding. As can be seen in Table 5.7, two coding tasks are not consistent in terms of the timing (6:50). A revised arbitrated coding should be added. Please refer to Appendixes H-2, I-2, J-2, and K-2 for the coding history.

To ensure the agreement of coding data, a comparison between the first and second versions of protocol coding is necessary. As can be seen in Table 5.8, the overall percentage of agreement between the first and second protocols is the lowest, 64%; the overall percentage of agreement between the first and the arbitrated protocols is the second, 76%; the overall percentage of agreement between the second and the arbitrated protocols is the highest, 80%. This indicates that the reliability of the arbitrated version of protocol is robust. The final arbitrated protocol, therefore, can serve as the basis for further statistical analysis.

Table 5.7: A fragment of the coding history

Time	First			Second			Arbitrated			Dialogue
	Pd	Mi	Ma	Pd	Mi	Ma	Pd	Mi	Ma	
5.04				Lp	Ps	Td	Lp	Ps	Td	It will be smooth when merged.
5.10	Lp	An	Td	Lp	An	Td	Lp	Ev	Td	It's tangent when the outer lines joined smoothly. It is, however, still on tracing process.
5.20	Lp	Dd	Td	Lp	La	Td	Lp	La	Td	The decorating scale detail will be dealt later. Now we will define the body.
6.13	Lp	Ps	Td							Select all lines.
6.50	Lp	An	Td	Lp	An	Td	Lp	Ev	Td	This part is not joined.
6.58	Lp	Ev	Td	Lp	Ev	Td	Lp	Ev	Td	There is some clearance.

Table 5.8: Coding consistency percentage between different versions of verbal protocols for four design episodes

Design Episode	1st &2nd	1st &Arbitrated	2nd & Arbitrated
A	62 %	76 %	78 %
B	70 %	80 %	79 %
C	65 %	69 %	80 %
D	57 %	78 %	82 %
Overall	64 %	76 %	80 %

5.4 Results and discussions of the coding for each design episode

According to the coding method mentioned earlier, the protocol for each design episode was made and tabulated. First of all, the time ratio of every category was calculated. The time ratio of a category is equal to the total time of a category to the total time of all categories in the Problem Domain, Micro Strategies, and Macro Strategies for Design Development and Model Construction tasks. Moreover, the distribution of all categories were calculated in terms of the time, so as to explore the thinking process designers use to manipulate the design activity in a CAID environment. The results of the statistical data for each design episode will be discussed in the following section.

5.4.1 Results of the protocol for design episode A

Based upon the raw protocol data of design episode A (Please refer to Appendix H-1), a final encoding of data was made (Appendixes H-3 and H-4). The Activity Chart (Appendixes H-5 and H-6) was then made in accordance with Appendixes H-3 and H-4 for observation and analysis. The model constructed for design episode A can be seen in Figure 5.9. The time the designer used for Design Development and Model Construction in design episode A is illustrated in Figure 5.10. The figure clearly shows us that the time the designer spent on Model Construction is much longer than that for Design Development. Accordingly, the activity frequency of Model Construction is much bigger than that of Design Development. That is to say, in a total of eight hours, the designer spent a lot of time and energy constructing the 3D model. The time for Design Development, therefore, was relatively shorter.

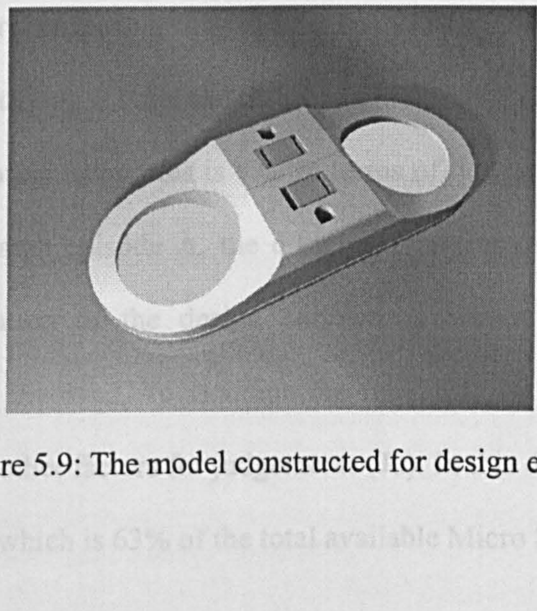

Figure 5.9: The model constructed for design episode A

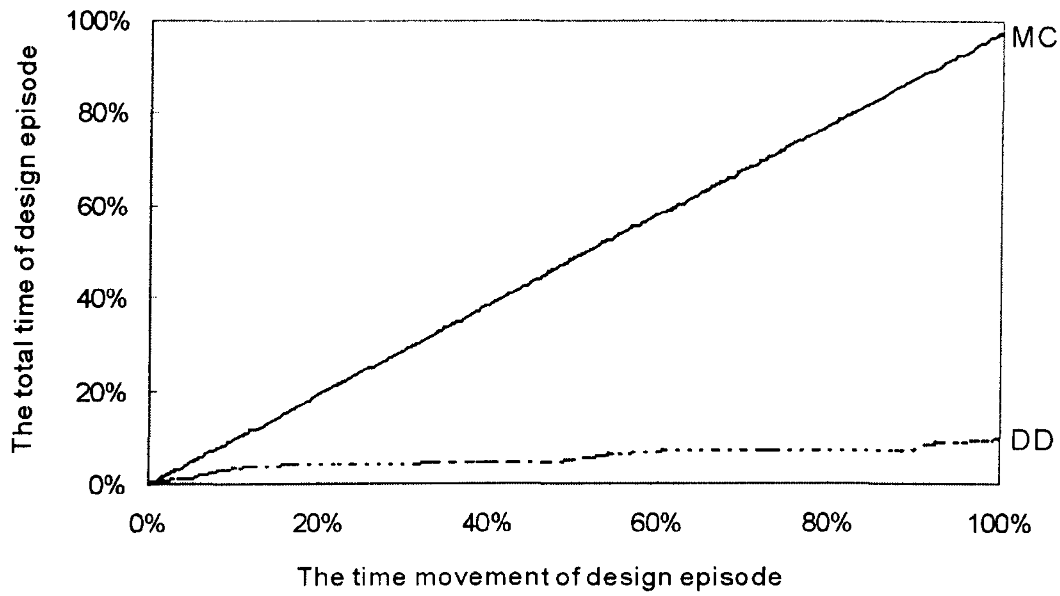

Figure 5.10: The time distribution curve (in percentage) of Model Construction (MC) and Design Development (DD) in design episode A

5.4.1.1 The result of design episode A in the Design Development task

The statistical data for Micro Strategies in Design Development in design episode A is shown in Figure 5.11. Amongst them, the time distribution for Evaluating a Proposed Solution (Ev) is the highest (33%). Other high categories, in decreasing order, are Proposing a Solution (Ps) (25%), Making a Design Decision (Dd) (24%) and Justifying a Proposed Solution (Ju) (10%). The total distribution time percentage for the other categories is 8%. In terms of design strategies in the Design Development of design episode A, the designer concentrated much more upon the making and evaluation of the design solution in which much decision-making behaviour (Dd) are involved. To examine the reliability of the evaluation task, the designer also chose other factors for judgements (Ju). In this design episode, 10 Micro Strategies are used, which is 63% of the total available Micro Strategies.

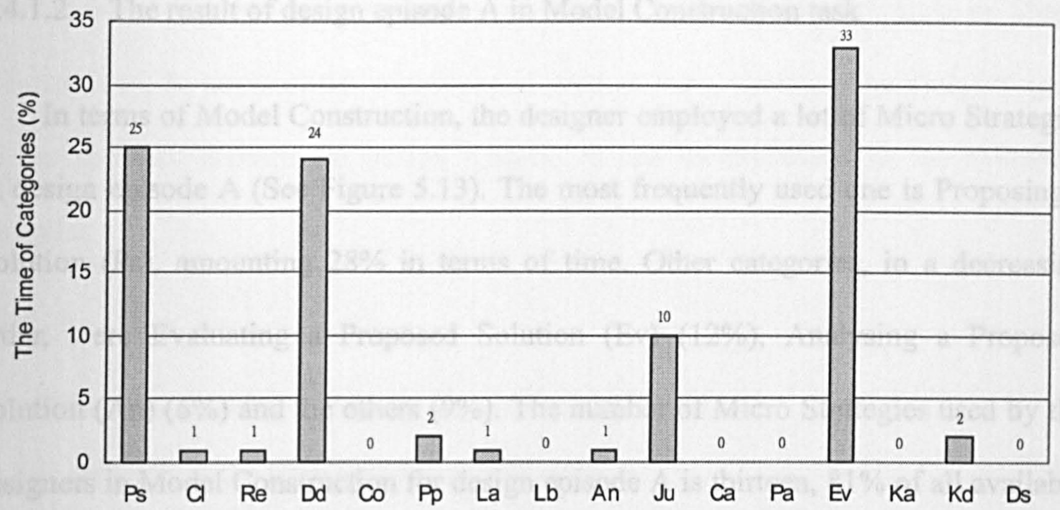

Figure 5.11: The time distribution (in percentage) of categories of Micro Strategies in the Design Development task (design episode A)

For the Problem Domain in Design Development, the designer was greatly concerned with the product form, size, texture, moulding, and functional problems (Figure 5.12). Of all the twenty-five problem categories, the designer considered only five, 20% of them.

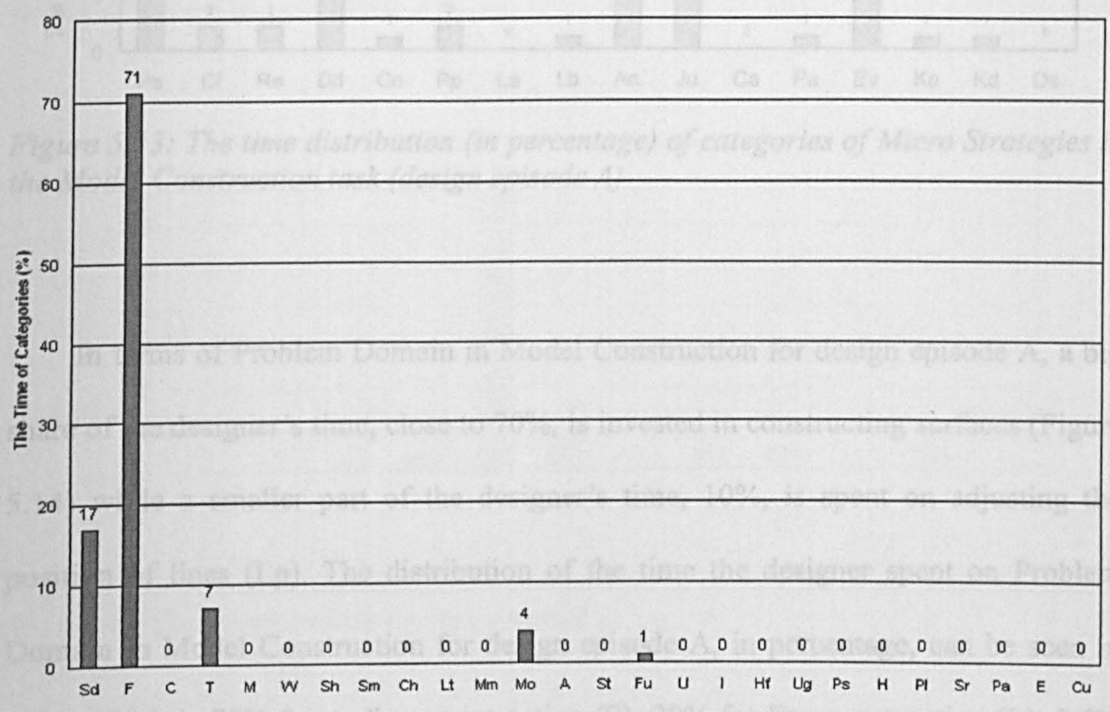

Figure 5.12: The time distribution (in percentage) of categories of problem domain in the Design Development task (design episode A)

5.4.1.2 The result of design episode A in Model Construction task

In terms of Model Construction, the designer employed a lot of Micro Strategies in design episode A (See Figure 5.13). The most frequently used one is Proposing a Solution (Ps), amounting 28% in terms of time. Other categories, in a decreasing order, were Evaluating a Proposed Solution (Ev) (12%), Analysing a Proposed Solution (An) (6%) and the others (9%). The number of Micro Strategies used by the designers in Model Construction for design episode A is thirteen, 81% of all available Micro Strategies.

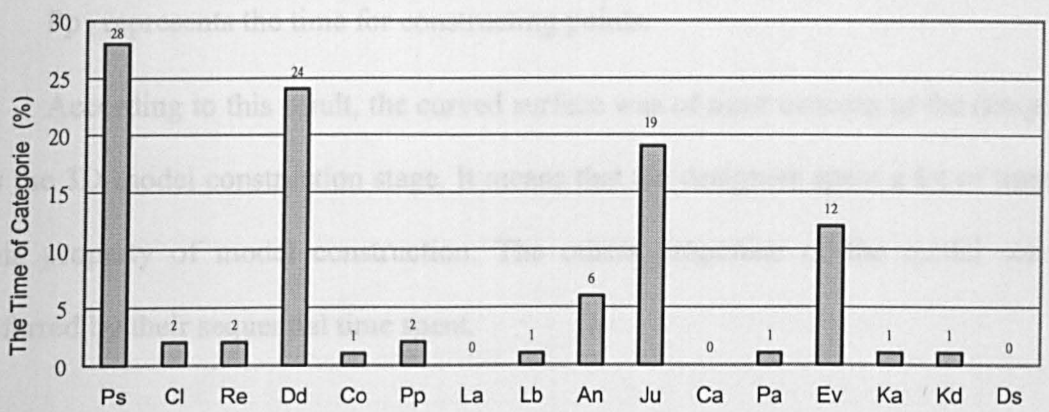

Figure 5.13: The time distribution (in percentage) of categories of Micro Strategies in the Model Construction task (design episode A)

In terms of Problem Domain in Model Construction for design episode A, a big share of the designer's time, close to 70%, is invested in constructing surfaces (Figure 5.14) while a smaller part of the designer's time, 10%, is spent on adjusting the position of lines (Lp). The distribution of the time the designer spent on Problem Domain in Model Construction for design episode A, in percentage, can be seen in Figure 5.14, is 75% for surface construction (S), 20% for line construction (L), 0.6% for edge construction (E), and 4.5% for product form (F). It is clear that the designer spent most of his energy in constructing surfaces in the problem domain of Model Construction. In terms of the primitives of product form, the time the designer spent in the problem domain for design episode A can be expressed as the following formula:

$S'_t > L'_t > F'_t > E'_t > Pp'_t$

Where S'_t represents the time for constructing surfaces;

L'_t represents the time for constructing lines;

F'_t represents the time for constructing product form;

E'_t represents the time for constructing edges;

Pp'_t represents the time for constructing points.

According to this result, the curved surface was of most concern to the designers in the 3D-model construction stage. It means that the designers spent a lot of time on this property of model construction. The others properties of the model can be inferred by their sequential time spent.

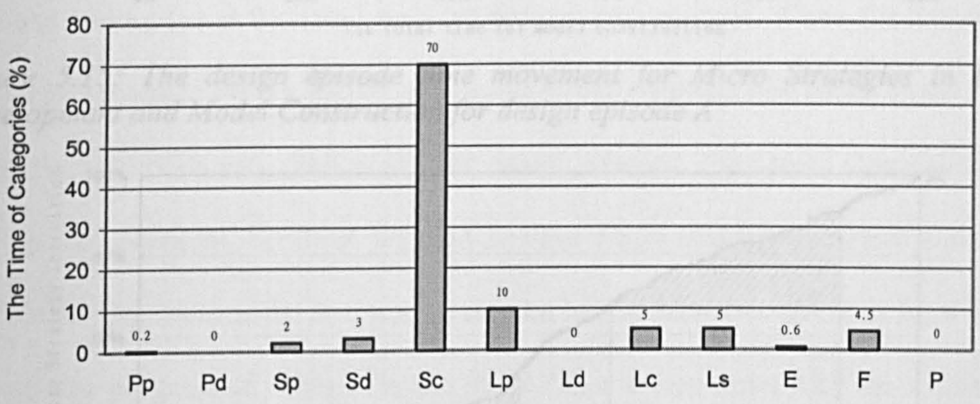

Figure 5.14: The time distribution (in percentage) of categories of problem domain in Model the Construction task (design episode A)

5.4.1.3 The comparison of time spent between Design Development and Model Construction in Micro Strategies for design episode A

In the application of Micro Strategies for design episode A, the time movement of Design Development and Model Construction was compared. According to the encoding protocol, the ratio of the time for Design Development to that for Model Construction is around 24% (Figure 5.15). The diagram of design episode time movement clearly shows that in two tasks (MC and DD), the time the designer spends on Micro Strategies for Design Development is much less than that for Model Construction.

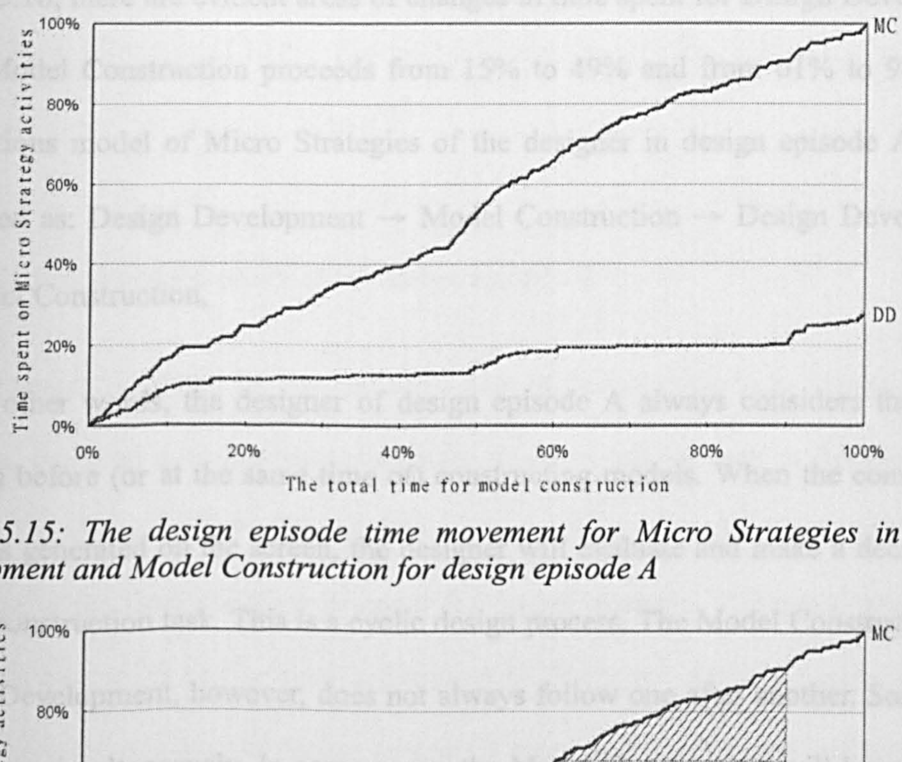

Figure 5.15: The design episode time movement for Micro Strategies in Design Development and Model Construction for design episode A

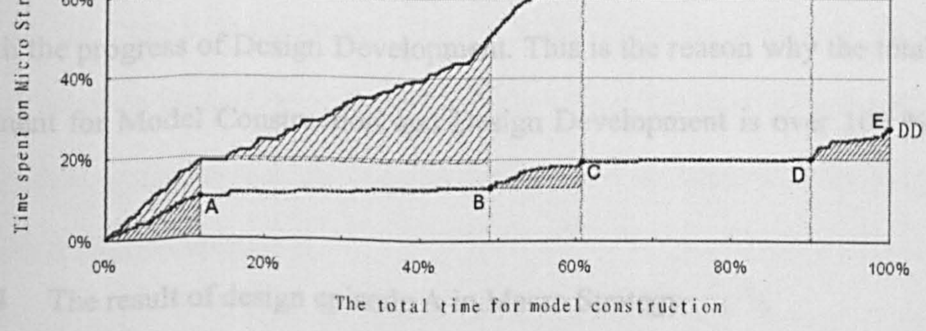

Figure 5.16: The evident increasing areas of design episode time movement for Micro Strategies in Design Development and Model Construction for design episode A

A close look at the time spent diagram shows that the time movement for Design Development is slow. In Figure 5.16, the three areas where there is an evident increase in time movement are marked. The first one is the beginning of the task, from 0% to 12%; the second one 49% to 61%; and the third one 90% to 100%. Comparing the patterns of time movement for Model Construction and Design Development tells us that the intense undertaking of Design Development will only happen after a long interval of Model Construction proceeding. For example, in Figure 5.16, there are evident areas of changes in time spent for Design Development when Model Construction proceeds from 15% to 49% and from 61% to 90%. The applications model of Micro Strategies of the designer in design episode A can be expressed as: Design Development → Model Construction → Design Development → Model Construction,

In other words, the designer of design episode A always considers the design problem before (or at the same time of) constructing models. When the construction output is generated on the screen, the designer will evaluate and make a decision for further construction task. This is a cyclic design process. The Model Construction and Design Development, however, does not always follow one after another. Sometimes they occur simultaneously. In some cases, the Model Construction will have a lot to do with the progress of Design Development. This is the reason why the total of time movement for Model Construction and Design Development is over 100 % (Figure 5.10).

5.4.1.4 The result of design episode A in Macro Strategy

According to the Activity Charts of Appendixes H-5 and H-6, there is important work for Model Construction in terms of Macro Strategy. It is found that top down strategy (Td) is the major strategy and opportunistic (Op) the minor. The evident change of Macro Strategy application indicates that the designer for design episode A has encountered many difficulties. The number of the applications of Op is up to thirty-two.

In terms of Design Development, there is no evident change of Macro Strategy application because the designer does not spend a long period of time on design episode A. There are 3 Ops. Generally speaking, Top Down strategy is the major application strategy.

5.4.2 Results of the protocol for design episode B

Appendix I-1 listed the raw protocol data of design episode B. Based upon the raw data, the final encoding protocols were made as can be seen in Appendixes I-3 and I-4. The Activity Chart (please refer to Appendixes I-5 and I-6) was then drafted according to the final encoding protocol for further analysis. The model constructed for design episode B can be seen in Figure 5.17. From the Activity Chart, it is clear that the time the designer of design episode B spent on Model Construction is longer than that on Design Development (Figure 5.18). Precisely speaking, the time the designer spent on Design Development is only 15% of the time the designer spent on Model Construction. It took the designer 2 hours and 40 minutes to finish the design activities for design episode B.

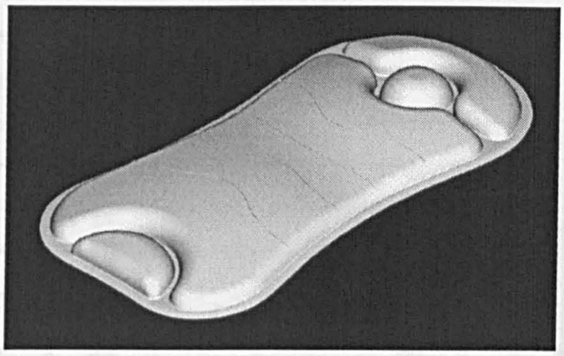

Figure 5.17: The model constructed for design episode B

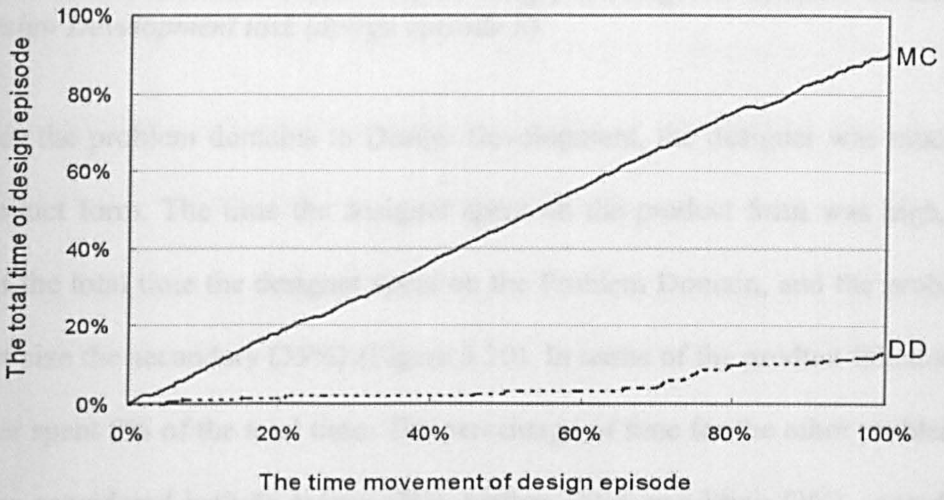

Figure 5.18: The time distribution curve (in percentage) of Model Construction and Design Development in design episode B

5.4.2.1 The result of design episode B in the Design Development task

Figure 5.19 shows the statistical data of Micro Strategy application in the Design Development of design episode B. The result indicates that three categories, Evaluating a Proposed Solution (Ev) (35%), Proposing a Solution (Ps) (25%), Justifying a Proposed Solution (Ju) (22%), were frequently applied by the designer doing design episode B. In addition, the categories Making a Design Decision (Dd) (16%) and Analysing a Proposed Solution (An) (2%) were not used so frequently. Generally, there were 5 items of Micro Strategy applied in the Design Development task, amounting 31% of the total categories.

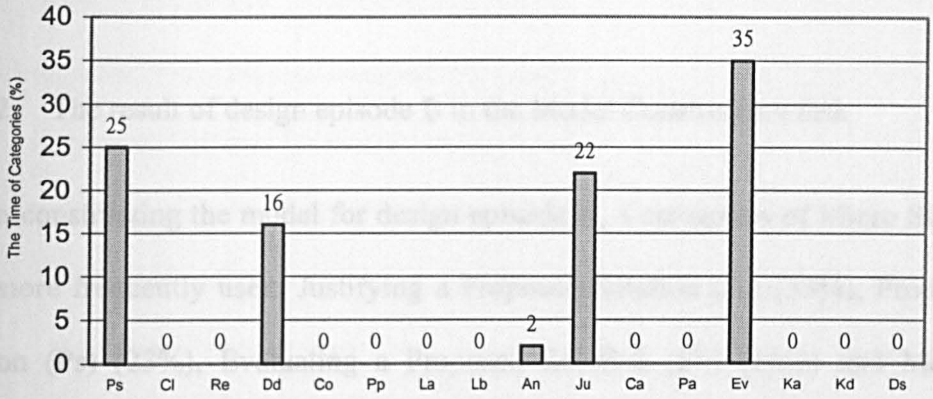

Figure 5.19: The time distribution (in percentage) of categories of Micro Strategies in the Design Development task (design episode B)

For the problem domains in Design Development, the designer was much with the product form. The time the designer spent on the product form was high, up to 49% of the total time the designer spent on the Problem Domain, and the problem of product size the secondary (33%) (Figure 5.20). In terms of the product functions, the designer spent 8% of the total time. The percentage of time for the other problems the designer considered include colour (2%), texture (2%), moulding (2%), manufacture (2%) and material (2%) ◦ The number of categories the designer was concerned with in Problem Domains is 8, about 32% of the total 25 categories.

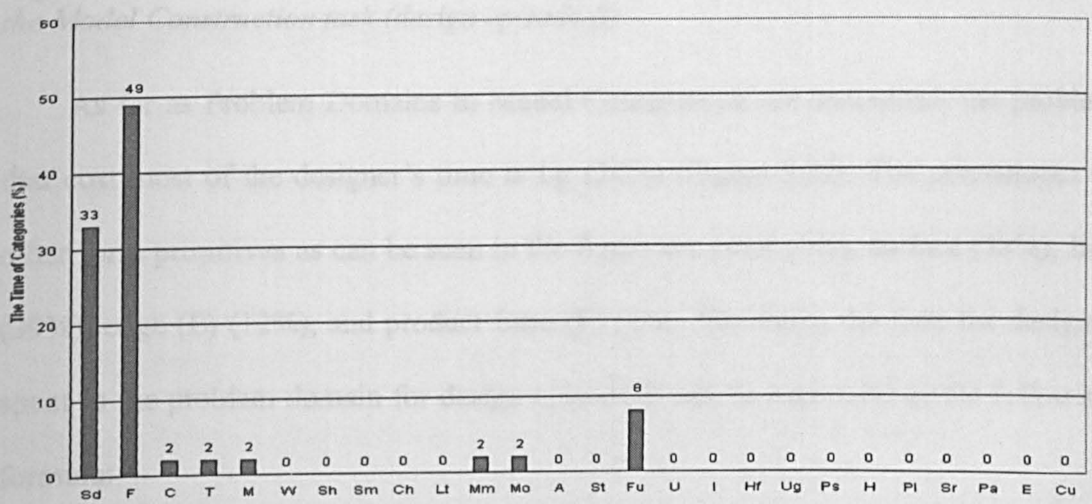

Figure 5.20: The time distribution (in percentage) of categories of problem domain in the Design Development task (design episode B)

5.4.2.2 The result of design episode B in the Model Construction task

In constructing the model for design episode B, 4 categories of Micro Strategies were more frequently used: Justifying a Proposed Solution (Ju) (33%), Proposing a Solution (Ps) (23%), Evaluating a Proposed Solution (Ev) (16%) and Making a Design Decision (Dd) (13%) (Figure 5.21). In addition, the designer employed Analysing a Proposed Solution (An) (7%) and another 4 strategies (8% in total for these 4 categories). The number of Micro Strategies the designer used in Model Construction is 9, about 56% of all 16 Micro Strategies.

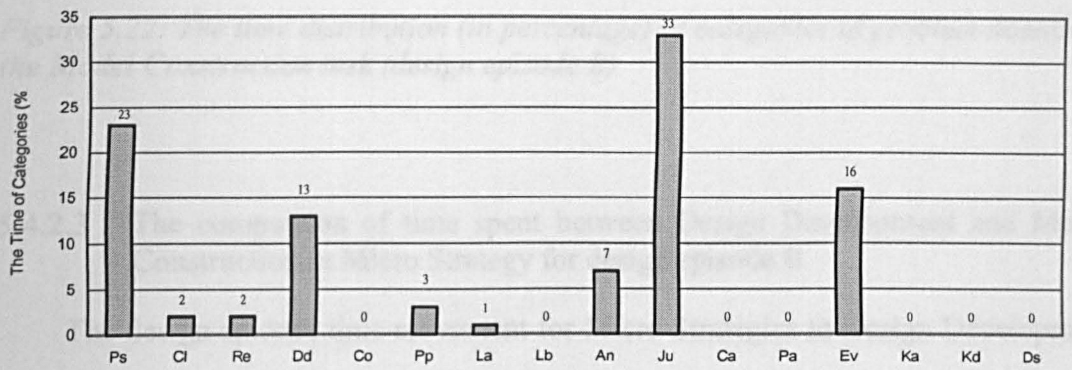

Figure 5.21: The time distribution (in percentage) of categories of Micro Strategies in the Model Construction task (design episode B)

As far as Problem Domains in Model Construction are concerned, the problem that cost most of the designer's time is Lp (24%) (Figure 5.22). The percentages of other form primitives as can be seen in the figure are point (9%), surface (38%), line (39%), edge (E) (12%), and product form (F) (2%). Generally, the time the designer spent in the problem domain for design episode B can be expressed as the following formula:

$$L'_t > S'_t > E'_t > P'_t > F'_t$$

L'_t represents the time for constructing lines;

S'_t represents the time for constructing surfaces;

E'_t represents the time for constructing edges;

P'_t represents the time for constructing points;

F'_t represents the time for constructing product form;

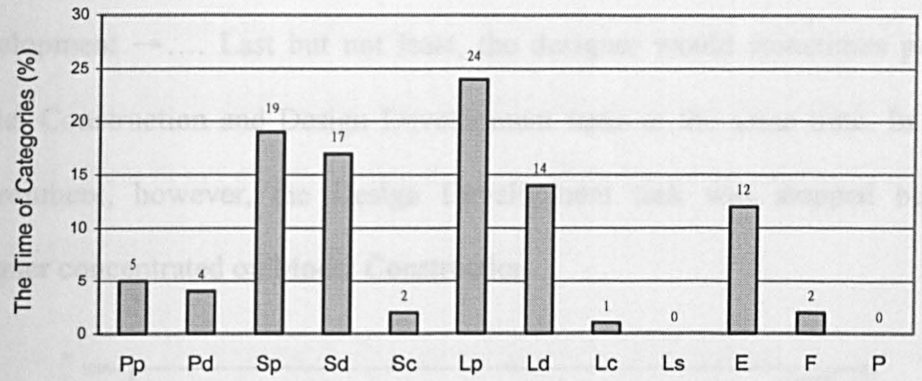

Figure 5.22: The time distribution (in percentage) of categories of problem domain in the Model Construction task (design episode B)

5.4.2.3 The comparison of time spent between Design Development and Model Construction in Micro Strategy for design episode B

The design episode time movement for Micro Strategies in Design Development and Model Construction for design episode B is shown in Figure5.23. Similar to that of design episode A, the time the designer spent on Design Development is only 35% of the time the designer spent on Model Construction. This confirms the result obtained from design episode B, the Model Construction task takes a lot more time than does the Design Development task.

Composing Figure 5.23 into Figure 5.24, it can be clearly seen that the designer started the Model Construction task earlier than the Design Development task. The designer started constructing a model, which was followed by a Design Development task from 4% to 7%, and then he continued the Model Construction task. There are four phases for the Design Development: the first one from 4% to 7%, the second one from 15% to 21%, the third one from 46% to 82%, and the fourth from 89% to 100%. Before the designer started the Design Development task, a certain period of time had been spent on Model Construction. The behaviour model for the design episode B is: Model Construction →Design Development → Model Construction → Design Development →.... Last but not least, the designer would sometimes perform the Model Construction and Design Development tasks at the same time. In the CAID environment, however, the Design Development task was stopped because the designer concentrated on Model Construction.

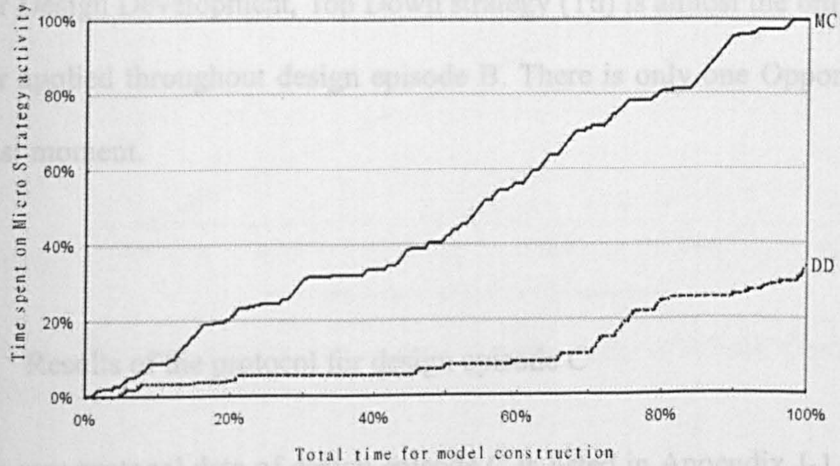

Figure 5.23: The design episode time movement for Micro Strategies in Design Development and Model Construction for design episode B

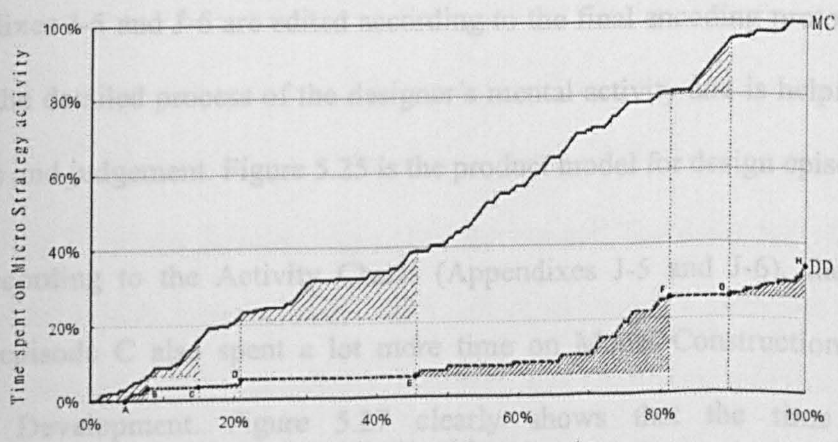

Figure 5.24: The evident increasing areas of design episode time movement for Micro

5.4.2.4 The result of design episode B in Macro Strategy

Based upon the Activity Charts in Appendixes I-5 and I-6, Top Down (Td) strategy is the major Macro Strategy for Model Construction. Besides this, there are 2 Decomposing the Problem (De) and 3 Opportunistic (Op) in the later stage. Generally speaking, there is not much change in Macro Strategy for the Model Construction of design episode B.

For Design Development, Top Down strategy (Td) is almost the only strategy the designer applied throughout design episode B. There is only one Opportunistic (OP) at the last moment.

5.4.3 Results of the protocol for design episode C

The raw protocol data of design episode C is listed in Appendix J-1 and the final encoding protocols are listed in Appendixes J-3 and J-4. Again, Activity Charts in Appendixes J-5 and J-6 are edited according to the final encoding protocol. It clearly shows the detailed process of the designer's mental activity and is helpful for further analysis and judgement. Figure 5.25 is the product model for design episode C.

According to the Activity Charts (Appendixes J-5 and J-6), the designer of design episode C also spent a lot more time on Model Construction than on the Design Development. Figure 5.27 clearly shows that the time for Design Development is only 10.5 % but that for Model Construction it is up to 90%. The total period of time the designer spent on design episode C is 2 hours 35 minutes.

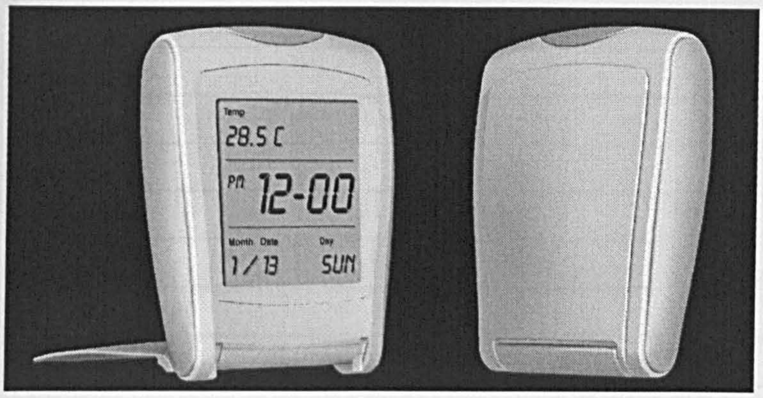

Figure 5.25: The model constructed for design episode C

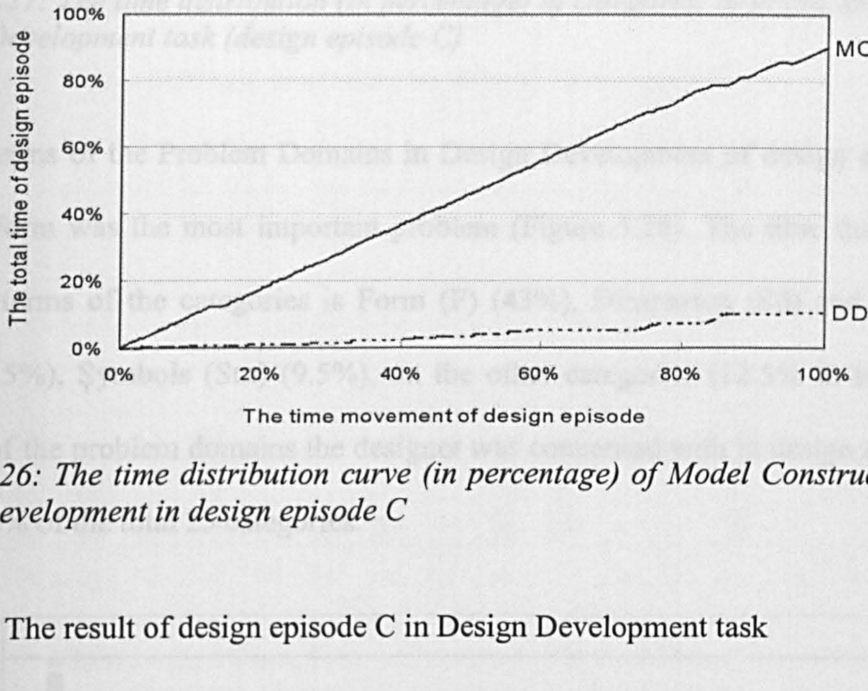

Figure 5.26: The time distribution curve (in percentage) of Model Construction and Design Development in design episode C

5.4.3.1 The result of design episode C in Design Development task

The statistical data for Micro Strategies in Design Development of design episode C is illustrated in Figure 5.27. In terms of the time the designer spent on the categories of Micro Strategy, Proposing a Solution (Ps) (42%) was the highest; Justifying a Proposed Solution (Ju) (23%) the second. The order for other categories was Evaluating a Proposed Solution (Ev) (19%), Analysing a Proposed Solution (An) (11%), Making a Design Decision (Dd) (3%), and Clarifying a Solution (Cl) (2%). There were 6 Micro Strategies the designer applied in design episode C, amounting to 38% of all 16 Micro Strategies.

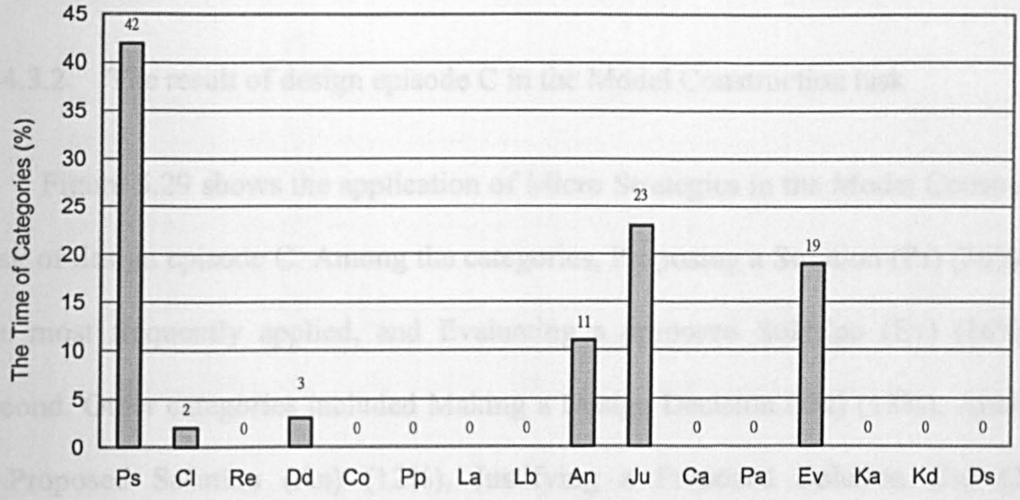

Figure 5.27: The time distribution (in percentage) of categories of Micro Strategies in Design Development task (design episode C)

In terms of the Problem Domains in Design Development of design episode C, product form was the most important problem (Figure 5.28). The time the designer spent in terms of the categories is Form (F) (43%), Dimension (Sd) and Part (Pa) (both 17.5%), Symbols (Sm) (9.5%), on the other categories (12.5% in total). The number of the problem domains the designer was concerned with in design episode C was 9, 36% of the total 25 categories.

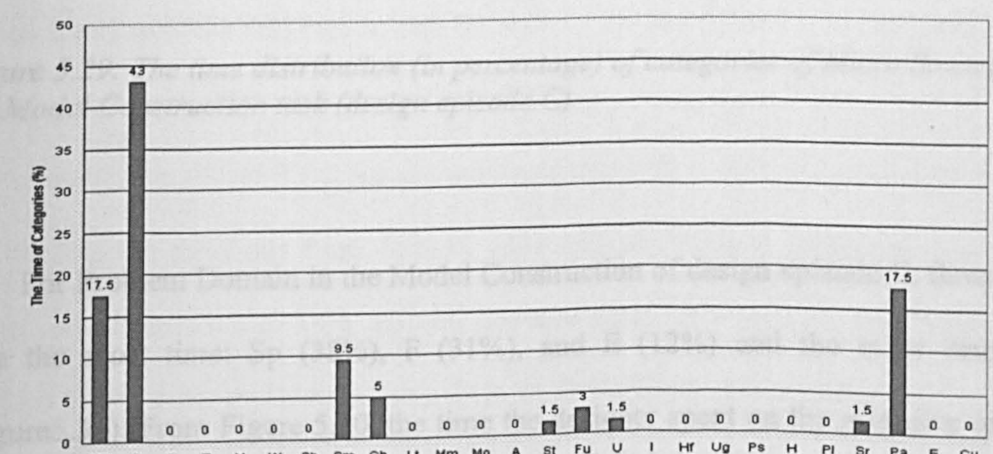

Figure 5.28: The time distribution (in percentage) of categories of problem domain in the Design Development task (design episode C)

5.4.3.2 The result of design episode C in the Model Construction task

Figure 5.29 shows the application of Micro Strategies in the Model Construction task of design episode C. Among the categories, Proposing a Solution (Ps) (36%) was the most frequently applied, and Evaluating a proposed Solution (Ev) (16%) the second. Other categories included Making a Design Decision (Dd) (13%), Analysing a Proposed Solution (An) (12%), Justifying a Proposed Solution (Ju) (10%), Clarifying a Solution (Cl) (8%) and the others (5% in total). The designer used 9 categories of Micro Strategy, amounting to 56% of 16 categories.

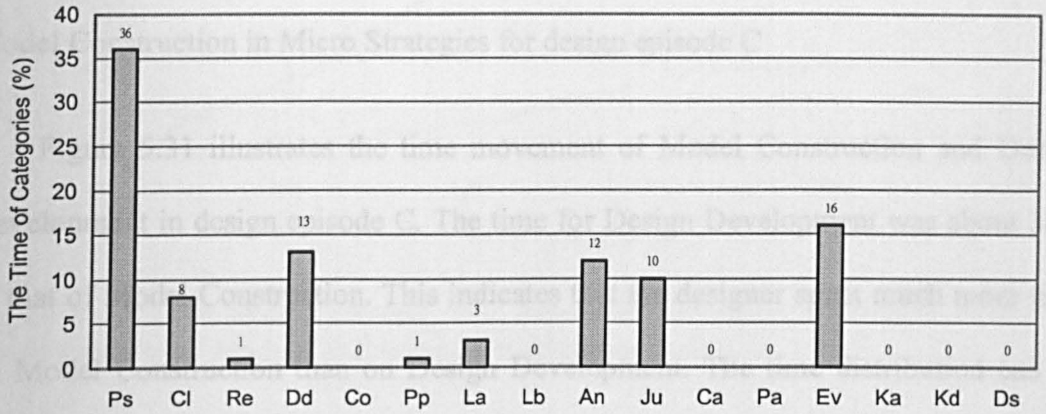

Figure 5.29: The time distribution (in percentage) of categories of Micro Strategies in the Model Construction task (design episode C)

For Problem Domain in the Model Construction of design episode C, three items take the most time: Sp (38%), F (31%), and E (12%) and the other items 9% (Figure5.30). From Figure 5.30, the time the designer spent on the primitive of form was, in decreasing order, Surface (43%), Form (31%), Edge (12%), and Line (14%), which can be denoted as: $S_t > F_t > L_t > E_t$.

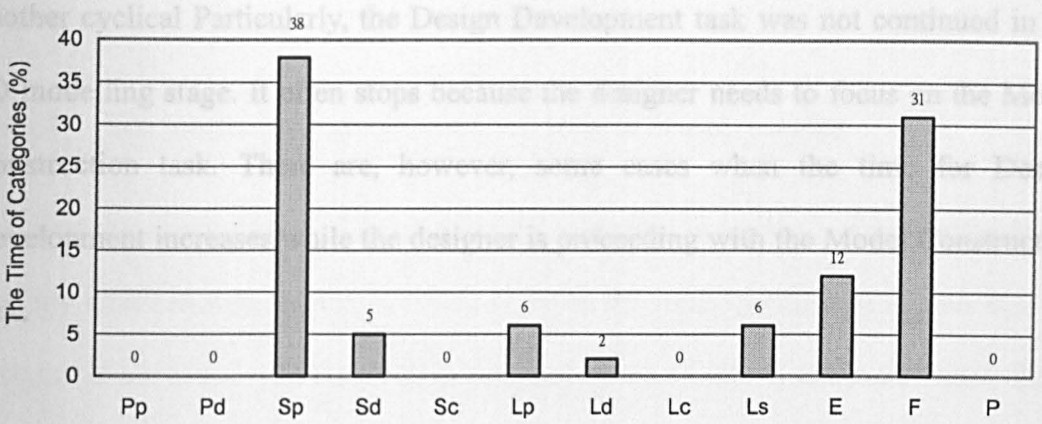

Figure 5.30: The time distribution (in percentage) of categories of problem domain in the Model Construction task (design episode C)

5.4.3.3 The comparison of time movement between Design Development and the Model Construction in Micro Strategies for design episode C

Figure 5.31 illustrates the time movement of Model Construction and Design Development in design episode C. The time for Design Development was about 38% of that of Model Construction. This indicates that the designer spent much more time on Model Construction than on Design Development. The time distribution can be transformed into the diagram as can be seen in Figure 5.32. From the diagram, the Design Development can be divided into 5 phases: the first one from 2% to 17% with an increase from 0% to 30%, the second one from 27% to 37% with an increase from 4% to 8%, the third one from 44% to 64% with an increase from 8% to 19%, the fourth one from 77% to 84% with an increase from 19% to 27%, and finally from 93% to 100% with an increase from 24% to 38%. There was almost no progress on the Design Development. On the contrary, the Model Construction continued except for very short periods. Similar to the other design episodes, the tasks of Model Construction and Design Development of design episode C was occurred one after another cyclical Particularly, the Design Development task was not continued in the 3D modelling stage. It often stops because the designer needs to focus on the Model Construction task. There are, however, some cases when the time for Design Development increases while the designer is proceeding with the Model Construction task.

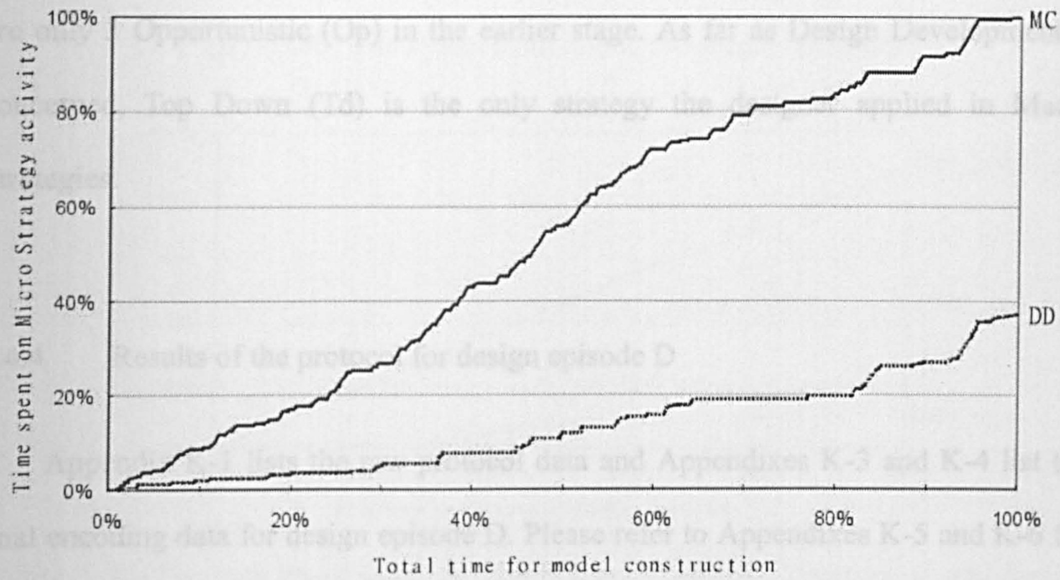

Figure 5.31: The design episode time movement for Micro Strategies in Design Development and Model Construction for design episode C

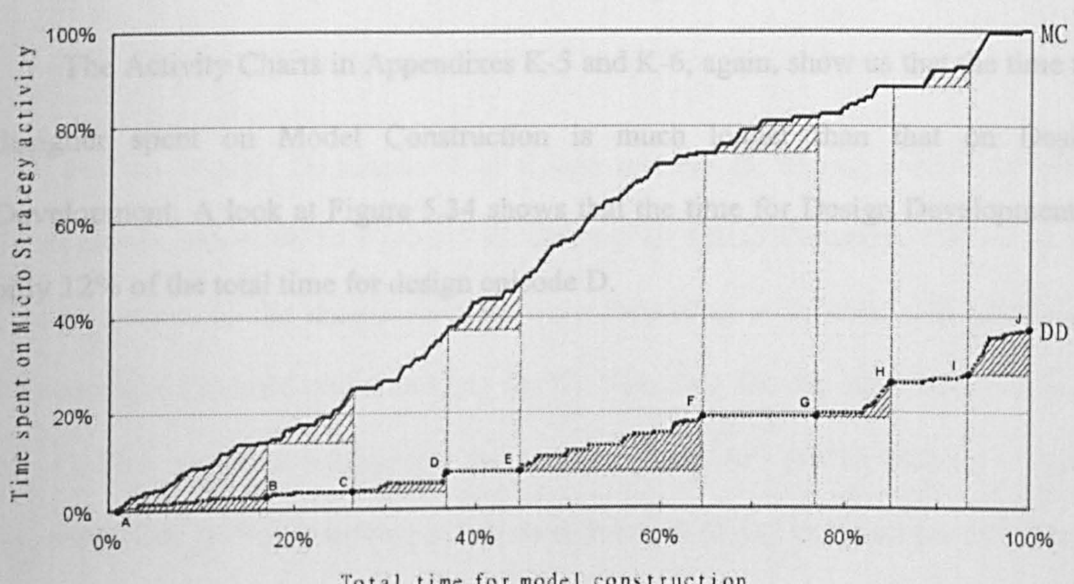

Figure 5.32: The evident increasing areas of design episode time movement for Micro Strategies in Design Development and Model Construction for design episode C

5.4.3.4 The result of design episode C in terms of Macro Strategy

For the application of Macro Strategy in design episode C, please refer to the Activity Chart in Appendixes J-5 and J-6. From the Activity Chart, it is clear that the designer tends to use Top Down (Td) category in the Model Construction task. There are only 3 Opportunistic (Op) in the earlier stage. As far as Design Development is concerned, Top Down (Td) is the only strategy the designer applied in Macro Strategies.

5.4.4 Results of the protocol for design episode D

Appendix K-1 lists the raw protocol data and Appendixes K-3 and K-4 list the final encoding data for design episode D. Please refer to Appendixes K-5 and K-6 for the Activity Charts for Model Construction and Design Development tasks. What can be seen in Figure 5.33 that is the model constructed for design episode D.

The Activity Charts in Appendixes K-5 and K-6, again, show us that the time the designer spent on Model Construction is much longer than that on Design Development. A look at Figure 5.34 shows that the time for Design Development is only 12% of the total time for design episode D.

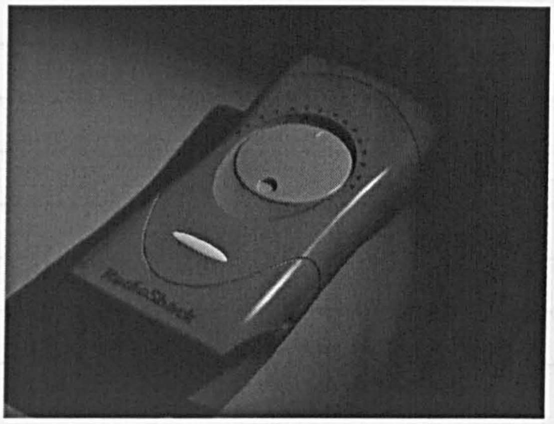

Figure 5.33: The model constructed for design episode D

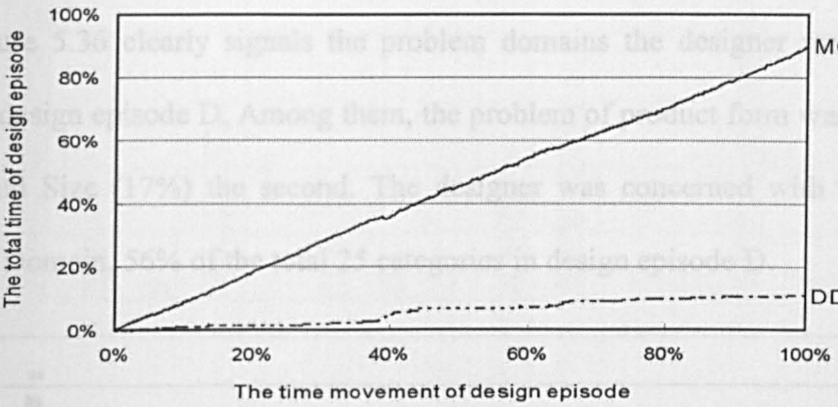

Figure 5.34: The time distribution (in percentage) of Model Construction and Design Development in design episode D

5.4.4.1 The result of design episode D in Design Development task

For the Design Development of design episode D, the application of Micro Strategies is illustrated in Figure 5.35. Among all Micro Strategies, the items that occupied most of the designer's time were Proposing a Solution (Ps) (24%) and Evaluating a Proposed Solution (Ev) (24%). The time for the other different items varied. They included Analysing a Proposed Solution (An) (14%). Making a Design Decision (Dd) (11%), Justifying a Proposed Solution (Ju) (11%), and the other items (16% in total). Of 16 Micro Strategies, the designer applied 9, 56% of them.

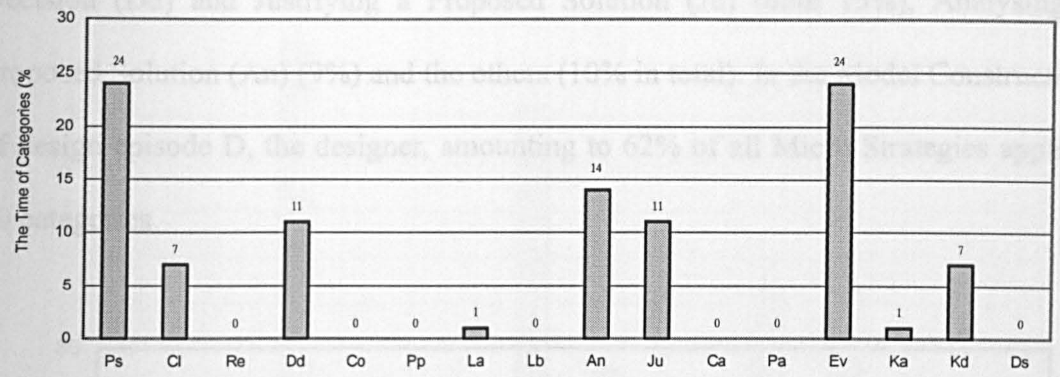

Figure 5.35: The time distribution (in percentage) of categories of Micro Strategies in the Design Development task (design episode D)

Figure 5.36 clearly signals the problem domains the designer was concerned with for design episode D. Among them, the problem of product form was the highest (39%) and Size (17%) the second. The designer was concerned with 14 items of Problem Domain, 56% of the total 25 categories in design episode D.

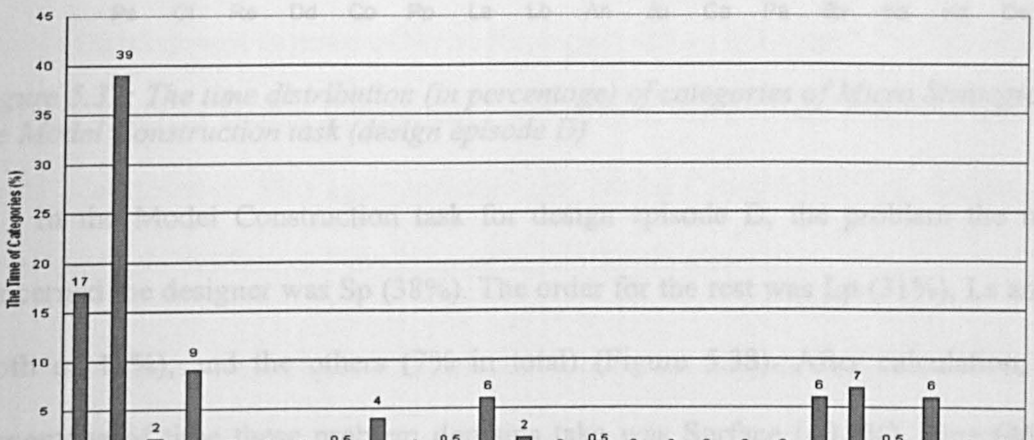

Figure 5.36: The time distribution (in percentage) of categories of problem domain in the Design Development task (design episode D)

5.4.4.2 The result of design episode D in Model Construction

In the application of Micro Strategies for the Model Construction task of design episode D (Figure 5.37), Proposing a Solution (Ps) (30%) was the highest, and Evaluating a proposed Solution (Ev) (21%) the second, followed by Making a Design

Decision (Dd) and Justifying a Proposed Solution (Ju) (both 15%), Analysing a Proposed Solution (An) (9%) and the others (10% in total). In the Model Construction of design episode D, the designer, amounting to 62% of all Micro Strategies applied 10 categories.

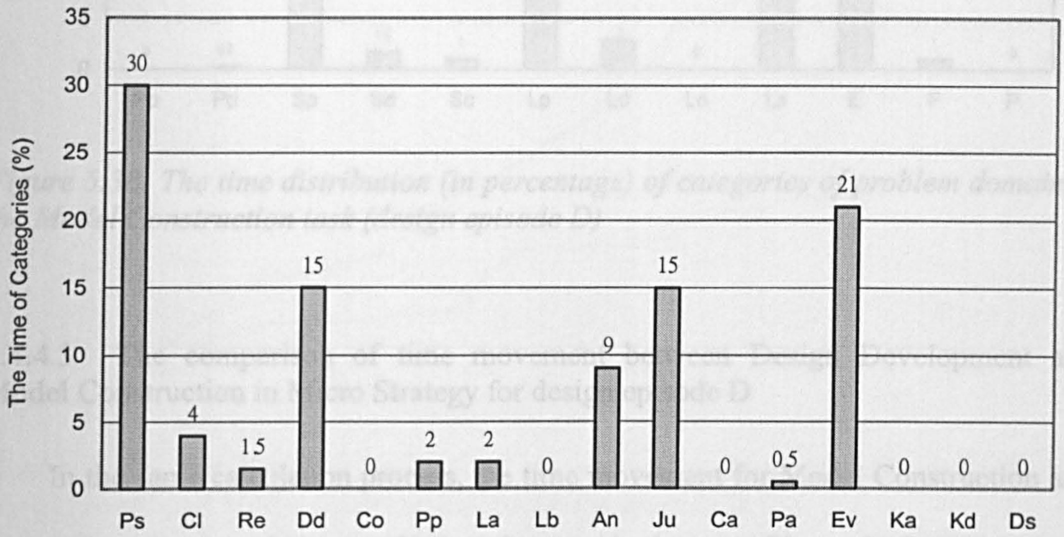

Figure 5.37: The time distribution (in percentage) of categories of Micro Strategies in the Model Construction task (design episode D)

In the Model Construction task for design episode D, the problem the most concerned the designer was Sp (38%). The order for the rest was Lp (31%), Ls and E (both of 12%), and the others (7% in total) (Figure 5.38). After calculation, the percentage of time these problem domains take was Surface (40.8%), Line (46%), Edge (12%), Form (F) (1%), and Point (0.2%). This is expressed as the following formula: $L'_t > S'_t > E'_t > F'_t > Pd'_t$.

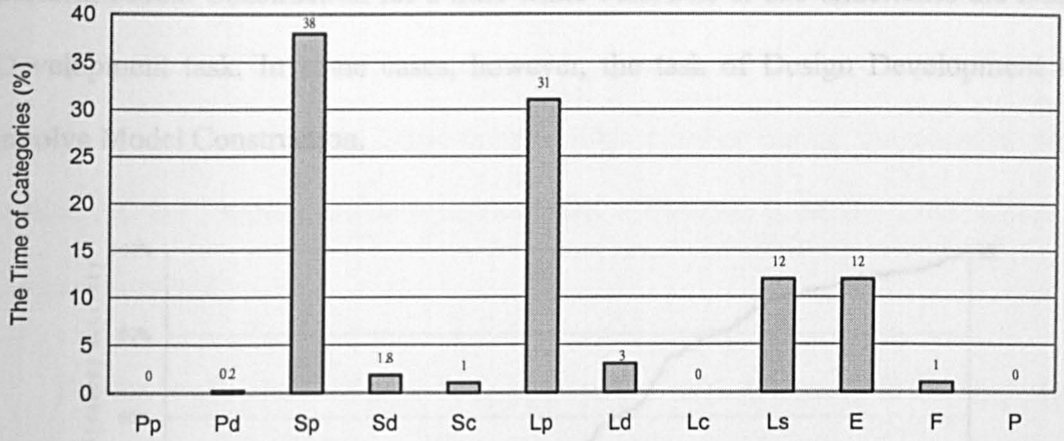

Figure 5.38: The time distribution (in percentage) of categories of problem domain in the Model Construction task (design episode D)

5.4.4.3 The comparison of time movement between Design Development and Model Construction in Micro Strategy for design episode D

In the same calculation process, the time movement for Model Construction and Design Development in terms of Micro Strategy is shown in Figure 5.39. The time the designer spent on Design Development was 39% of the time the designers spent on Model Construction. This again indicates that Model Construction cost the designer more time than did Design Development in this design episode.

Transformed from Figure 5.39, the time movement diagram in Figure 5.40 shows that there are four phases in Design Development where the increase of Micro Strategy application is evident. The first phase falls in the range from 2% to 17%, with an increase from 0% to 5%; the second one from 27% to 43% with an increase from 5% to 23%, the third one from 58% to 78% with an increase from 23% to 36%, and finally, from 68% to 100% with an increase from 36% to 39%. The characteristic of the time movement distribution reflects the designer's cyclic behaviour model, which can be denoted as Model Construction→Design Development→Model Construction→Design Development→.... That is to say, the designer will first perform Model Construction for a little while before he or she undertakes the Design Development task. In some cases, however, the task of Design Development will involve Model Construction.

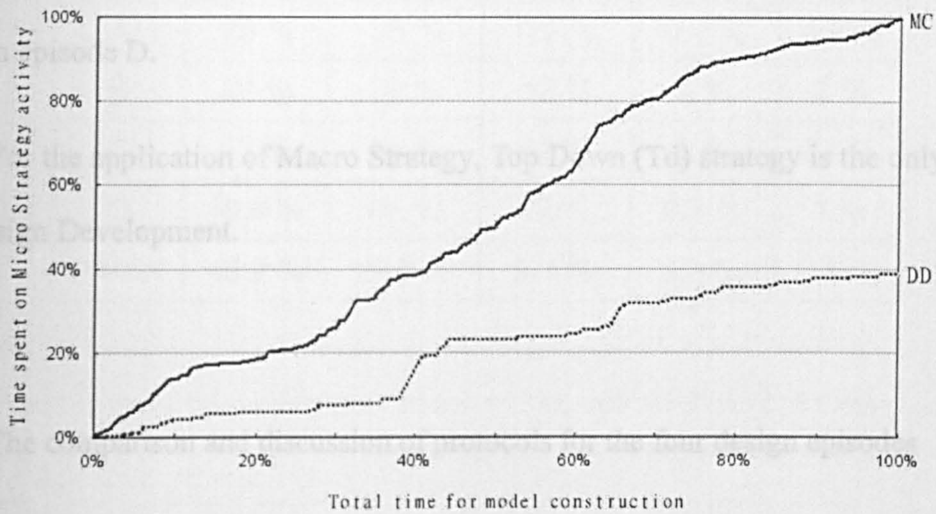

Figure 5.39: The design episode time movement for Micro Strategies in Design Development and Model Construction for design episode D

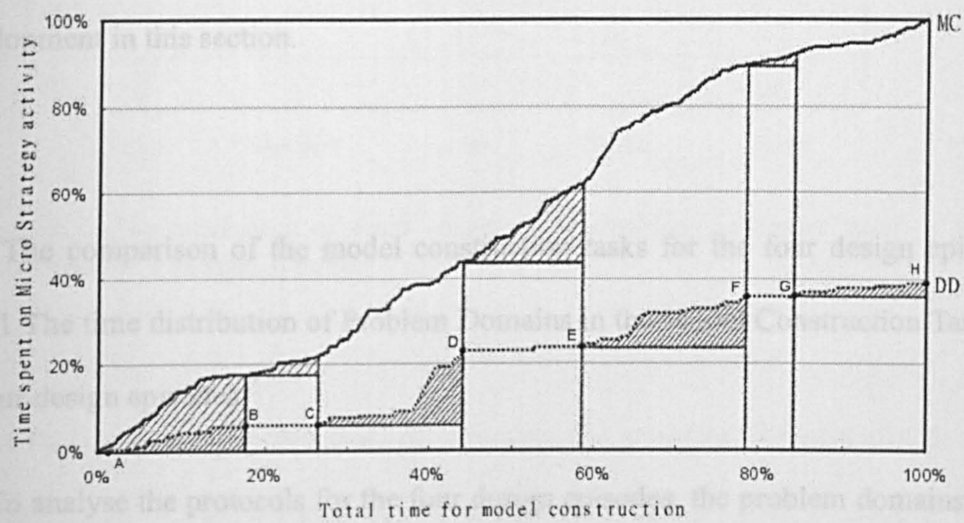

Figure 5.40: The evident increasing areas of design episode time movement for Micro Strategies in Design Development and Model Construction for design episode D

5.4.4.4 The result of design episode D in Macro Strategy

The Activity Charts shown in Appendixes K-5 and K-6 reflect the change of

Macro Strategy application in design episode D. From the diagram of the Activity Chart, Top Down (Td) was the major thinking process for Model Construction tasks. Besides this, there were 14 Opportunistic (Op) existing during the process, which means that the designer had encountered many difficulties in Model Construction for design episode D.

For the application of Macro Strategy, Top Down (Td) strategy is the only choice in Design Development.

5.5 The comparison and discussion of protocols for the four design episodes

Based upon the results of statistical data in Section 5.4, the four design episodes will be compared and discussed in terms of Model Construction and Design Development in this section.

5.5.1 The comparison of the model construction tasks for the four design episodes

5.5.1.1 The time distribution of Problem Domains in the Model Construction Task for the four design episodes

To analyse the protocols for the four design episodes, the problem domains have been classified into five groups: Point (Pp, Pd), Surface (S), Line (L), Edge (E), and Form (F). According to the statistical data previously mentioned, the time distribution for each category of Problem Domains used in the Model Construction for 4 design episodes is shown in Table 5.9 and Figure 5.41 (in the next page).

Table 5.9: The time distribution of each category of Problem Domains used in Model Construction for 4 design episodes

DE= Design Episode

PD / D.E.	Surface	Line	Edge	Point	Form
A	75 %	20 %	0.6 %	0.2 %	4.5 %
B	38 %	39 %	12 %	9 %	2 %
C	43 %	14 %	12 %	0 %	31 %
D	40.8 %	46 %	12 %	0.2 %	1 %
Average	49.2 %	29.8 %	9.1 %	2.3 %	9.6 %

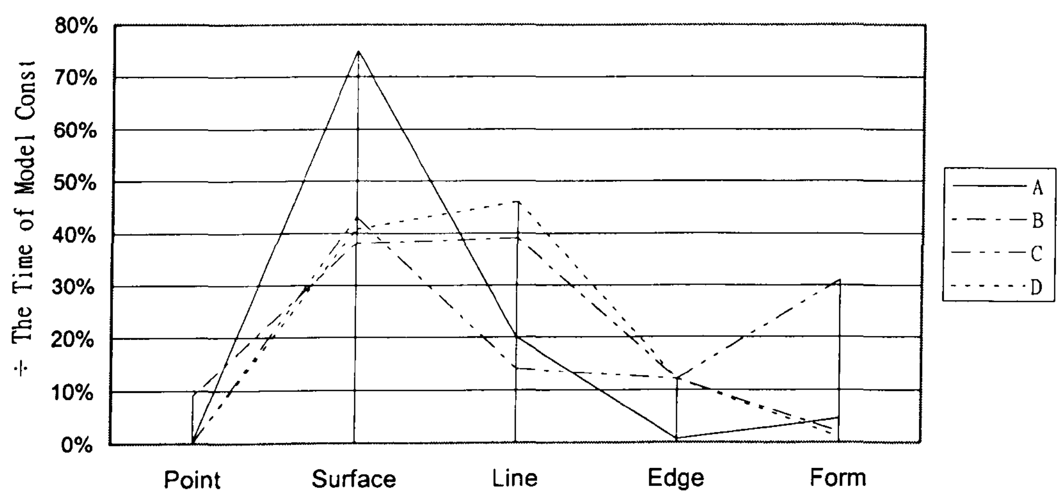

Figure 5.41: The total time of each category of Problem Domains used in Model Construction for 4 design episodes

Table 5.9 clearly shows that, on average, the problem domains the designer concentrated on in Model Construction were, in decreasing order, Surface (49.2%), Line (29.8%), Form (9.6%), Edge (9.1%), and Point (2.3%). Though the average of the total time for Product Form (9.6%) was higher than that for Edge (9.1%), it is not always the case. In Figure 5.41, the total time spent on Form in design episode C was high up to 31%, which did not really reflect the actual condition. Checking the final protocol encoding data of Appendix J-3 and Figure 5.31, we know that the Model

Construction stopped at the later stage (about 95% through the total Model Construction time) because the designer transferred the initial 3D render output to PhotoShop for the image processing to save time. Although the Model Construction task actually stopped, the encoder classified the Problem Domain to Product Form. If this period of time for Model Construction in design episode C is deleted, the time the designer spent on product form should be 7% rather than 31%. Consequently, the average time of 4 design episodes for Product Form is 3.6%.

The result of the statistical data mentioned above indicates that the designer or computer operator spends the longest time constructing surfaces in 3D Model Construction. The other point is that surface construction takes the designer or computer operator much more effort. According to the protocols of the 4 design episodes, the Model Construction starts with the identification of the point's position, which will help specify the location and size of lines. Based upon the relative position of several lines, the designer or computer operator can begin making the surfaces. After surfaces are complete and the initial model has met the requirement of product form, the construction or revising of Edge, for example, filleting a single rounded edge or a gradient rounded edge, will then take place. The Model Construction task under the CAID environment, therefore, follows the model of Points→ Lines → Surfaces → Edges.

The actual average time the designer or computer operator is involved with Product Form is 3.6%. This does not however indicate that the designer or computer operator does not care about the Problem Domain of product form. On the contrary, Product Form is the real purpose of the Model Construction and has been gradually achieved in the construction of Points, Lines, Surfaces and Edges. The fact that Form takes only 3.6% of the total Model Construction time actually represents the time the designer or computer operator spends in revising the whole product form, after the initial form is finished. It does not include the time the designer spends evaluating whether the product form meets the requirements of aesthetics. This kind of issue belongs in the area of Design Development, but not in the Problem Domains of the Model Construction task.

5.5.1.2 The time distribution of Micro Strategy application in the Model Construction Task for the four design episodes

Figure 5.42 illustrates the time distribution of Micro Strategy application in the Model Construction Task of the four design episodes. The main categories the designers apply in the 4 design episodes are to Proposing a Solution (Ps), Justifying a Proposed Solution (Ju), Making a Design Decision (Dd), Evaluating a Proposed Solution (Ev) and Analysing a Proposed Solution (An). How to start the Model Construction task is on intuitive response for the designers or computer operators because they are familiar with the software to a certain degree. It is like unlocking a digital lock. All the operator needs to do is to retrieve the digit from the memory. The designer or computer operator, therefore, often proposes a solution, and decides to proceed with the Model Construction task (See the Activity Chart of Model Construction in Appendixes). When the knowledge and methodology for Model Construction does not reach the expected goal, the designer will try to generate some other new ways to solve the design problem and undertake the analysis and evaluation before the initiation of the Model Construction task. In this case, the designer works like a human being processing information (Lachman, 1979). That is to say, the graphics shown on the monitor are a sort of stimulus that draws the attention of designers or computer operators. They will perceive the stimulus, think it over, make a decision, and take a certain responding reaction (Figure 2.12). Such a kind of Model Construction task is partly influenced by the model construction methods of CAID systems of computers. According to much psychological research, parts of function of human brain are similar to that of the computer, which is Top Down model (Bruner and Postman,1949; Marr, 1982; Eysenck, 1993).

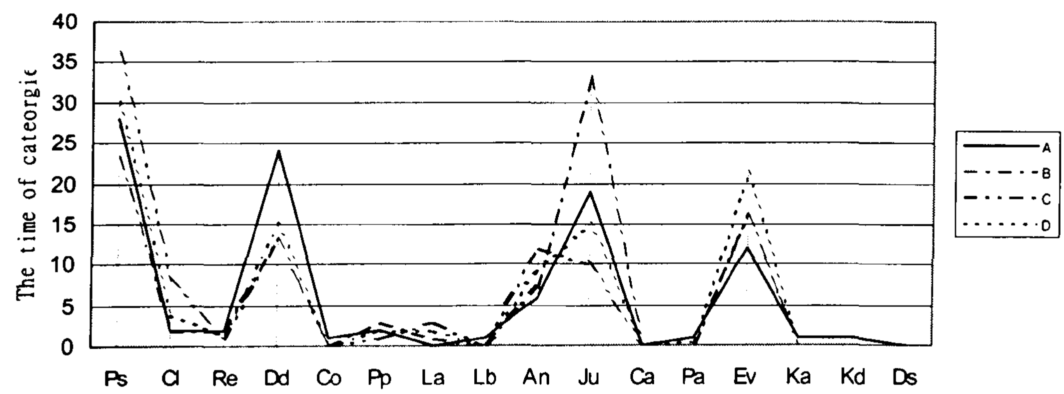

Figure 5.42: The time distribution of each category of micro strategies in model construction for the 4 design episodes

From the Activity Chart of Model Construction, the designer or computer operator will sometimes stop unexpectedly and do nothing in terms of micro strategy. This is happen a couple of times in the design episode A at 26 minutes, 2 hours 30 minutes, and 5 hours 30 minutes (see Appendix H-5). This may be due to the fact that the designer or computer operator relies too much on an intuitive response for deciding Model Construction strategy to propose their solutions. When the difference between the output data on the monitor and the designer's or computer operator's expected goal is increasing, the designer or computer operator will go into a status of so-called absent-mindedness (Shiffrin and Schneider, 1977). In cognitive engineering, the cause of the reduction in attention of vigilance is still unknown (Mackworth, 1950; Broadbent, 1971). Based upon the observation of the Model Construction, it can be inferred that when the designer or computer operator encounters several trials and errors, and at the same time their knowledge and skills can not support their possible solutions, such a phenomenon will happen.

Analysing the Activity Chart of Model Construction (Appendixes H-5, I-5, J-5, and K-5) in terms of the professional background and experience, some interesting findings are discovered. Constructing the model for design episode D takes the designer about 6.25 hours. The frequency of the application of Micro Strategies during the construction task is high, up to 2.5 segments every minute. Its average frequency is higher than in the other design episodes, design episode A is 2.01, design episode B is 1.52, and design episode C is 1.03. In terms of the professional background of the subjects, there is one designer and one computer operator for design episodes B and D (Table 5.2). When two persons work together, they have to communicate with each other frequently. The frequency of the communication in design episodes for the two workers, therefore, will be higher than that of the design episodes for only one worker. In addition, one of the members of design episode D is an experienced industrial designer (15 years of experience) and the other is a junior computer operator (1 year of experience). When they work together, there is a pretty high frequency of communication between them. The computer operator has to not only spend a lot of effort trying to understand the intention and thinking processes of the experienced designer, but also to execute the Model Construction task with the software he is not very familiar with. Such interactions between co-workers and between the operator and computer will take a lot of effort and will happen very frequently. This is the reason why the application frequency of Micro Strategy is high up to 2.5 each minute and the number of Micro Strategies used is up to 62% (Figure 5.43). In light of this, the application frequency and the number of Micro Strategies used in design episode B is lower, because the subjects for design episode B consist of an industrial designer of 12 years experience and a computer operator of 5 years experience. The total time for finishing design episode B is only 2.6 hours and the application frequency of Micro Strategies in Model Construction is 1.52 each minute. The Activity Chart in Appendix J-5 can confirm this. Moreover, the number of Micro Strategies used by the subjects of design episode B is only 56% (Figure 5.43), and is also lower than that of design episode D. The result indicates that, in a CAID environment, the Model Construction of a design episode where an experienced designer and a computer operator work together, will be more efficient than that of the designer and computer operator with less experience in terms of frequency and time for communication. In all the Activity Charts of design episodes B and D, the two groups are similar to each other because both of them applied Micro Strategies very often at the beginning of Model Construction. This phenomenon indicates that at the early stage of Model Construction, the frequency of interactive communication between different professions will be higher. This is because they need to understand each other's intention and to delete conflicting ideas, so the frequency of Micro Strategy application is relatively higher.

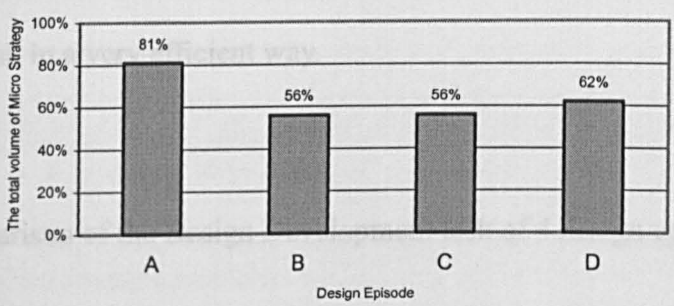

Figure 5.43: The percentage of the micro strategies used in model construction for 4 design episodes

The Model Construction task of design episode A is performed by a young industrial designer. The frequency with which he applied Micro Strategy in Model Construction is 2.01 every minute, which is second only to the team of design episode D (2.5 every minute). In addition to the high frequency of Micro Strategy application, the designer spent much longer time (8.75 hours) on the task and used a wide variety of Micro Strategies (81%) (Figure 5.43). It is evident that the young designer could not accomplish the expected goal in a short period of time, partly because he was not adept at controlling the computer, and partly because he worked independently. Though the product form of design episode A is the simplest and the easiest to construct of all four design episodes, the young designer spent a lot of time figuring out how to accomplish the task.

The product form of design episode C is a little more complex than that of design episode A. Because the designer had 3 years' experience in operating computer software, the frequency of Micro Strategy application is 1.03 every minute and the categories of Micro Strategies is 56%. The frequency and category number of Micro Strategy application are lower than those of the other 3 design episodes are. As a matter of fact, the designer expressed that he had thought about how to construct the model efficiently the night before. Therefore, it seems that he performed the Model Construction task in a very efficient way.

5.5.2 The comparison of the Design Development task of 4 design episodes

5.5.2.1 The time distribution of Problem Domains of the Design Development of 4 design episodes

Based upon the statistical data of Problem Domains for the Design Development of the 4 design episodes in Section 5.4, Figure 5.44 is obtained. The result shows that Product Form (F) is the problem the subjects in the 4 design episodes paid most attention to. Other problems, which the subject placed more emphasis on in the 4 design episodes, were texture, moulding, and function. The Problem Domains for Design Development in the 4 design episodes are shown in Figure 5.45 according to the statistical results in Section 5.4. Figure 5.45 makes it clear that the categories of Problem Domains for Design Development considered by the subjects of design episode D are the widest (56%), and that of design episode A are the narrowest (20%). It is 36% in design episode C and 32% in design episode B. Comparing this data in terms of the designer's experience indicates that the design problems considered by experienced designers in a CAID environment, are more comprehensive than those by the junior designers. The junior designers pay attention to problems about product form (design episode A in Figure 5.44). They less frequently consider other design problems.

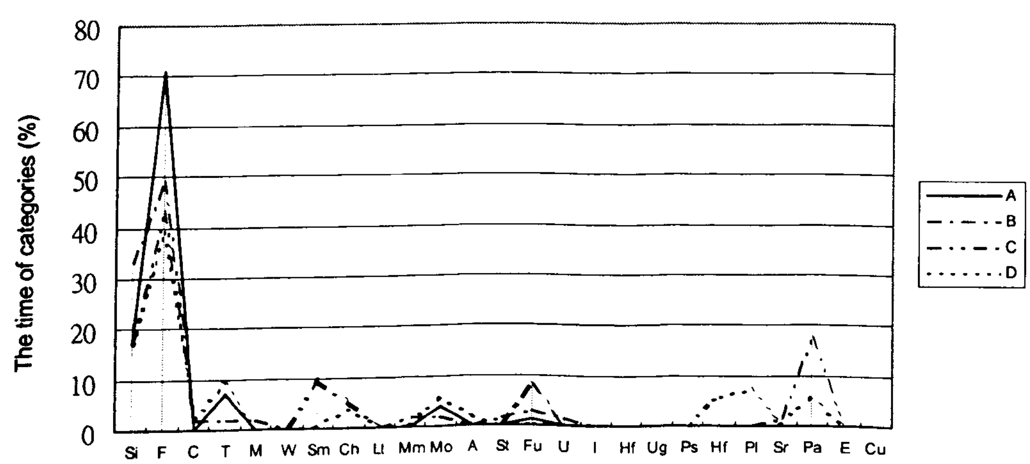

Figure 5.44 The time distribution of each category of problem domains in design development for the 4 design episodes

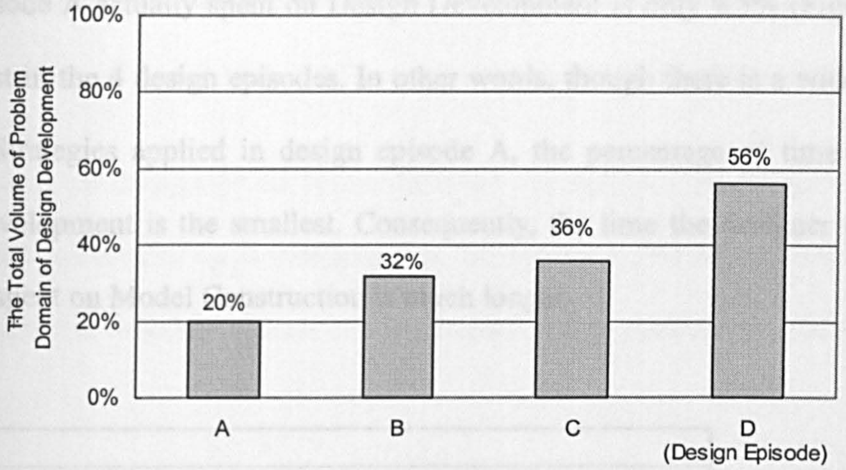

Figure 5.45 The percentage of problem domains considered in design development for the 4 design episodes

5.5.2.2 The time distribution of Micro Strategy application in the Design Development task of the 4 design episodes

In the 4 design episodes, the Micro strategies applied in Design Development are Proposing a Solution (Ps), Making a Design Decision (Dd), Analysing a Proposed Solution (An), Justifying a Proposed Solution (Ju), and Evaluating a Proposed Solution (Ev) (Figure 5.46). The range of categories of Micro Strategies applied in the Design Development of the 4 design episodes in illustrated is Figure 5.47. Of the 4 design episodes, design episode A has the highest value (63%), which indicates that the designer made a lot of effort in Design Development. The categories of Micro Strategy applied in design episode D is also high (56%), but those of the other two design episodes; B and C are lower. Considering the subject's experience in design, it can be inferred that the junior designers do not take as many things into consideration as the experienced designers. For example, in some design problems it is not easy to find 2D forms of your ideas in the CAID environment. The young designer in design episode A, therefore, needed to consider a lot of these problems, causing the range of categories of Micro Strategy to be wider. However the time the young designer in design episode A actually spent on Design Development is only 9.5% (Figure 5.10), the smallest in the 4 design episodes. In other words, though there is a wider variety of Micro Strategies applied in design episode A, the percentage of time spent on Design Development is the smallest. Consequently, the time the designer of design episode A spent on Model Construction is much longer.

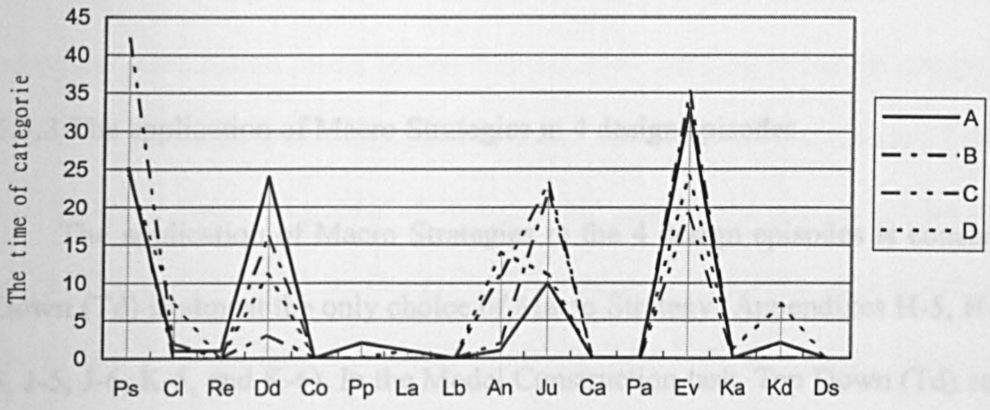

Figure 5.46: The time distribution of each category of micro strategy in design development for 4 design episodes

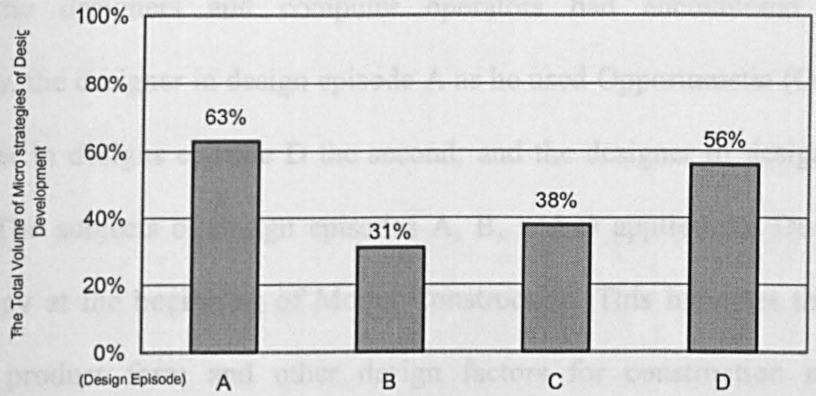

Figure 5.47: The percentage of the micro strategies used in design development for the 4 design episodes

The range of categories of Micro Strategy applied in design episode D is up to 56%. From the Activity Chart in Appendix K-6 and the final encoding protocols (Appendix K-4), the experienced industrial designer will spend some time explaining the design problem to the junior computer operator, in order to make the computer operator understand why some details of the 3D models in CAID systems need to be changed or adjusted, so that there will be a smooth flow in Model Construction.

The range of categories of Micro Strategy the designer in design episode B applied is the lowest (31%). It indicates that the experienced designer and computer operator can finish their job without considering the design problem too much.

5.5.3 The application of Macro Strategies in 4 design episodes

The application of Macro Strategies in the 4 design episodes is consistent. Top Down (Td) is almost the only choice of Macro Strategy (Appendixes H-5, H-6, I-5, I-6, J-5, J-6, K-5, and K-6). In the Model Construction task, Top Down (Td) strategy as well as Opportunistic (Op) strategy is employed in the 4 design episodes. This means that all the designers and computer operators had encountered difficulties. Particularly, the designer in design episode A as he used Opportunistic (Op) the most; the designer in designs episode D the second; and the designer of design episode C the least. The subjects of design episodes A, B, and D applied the Decomposition (De) strategy at the beginning of Model Construction. This indicates that they had taken the product form and other design factors for construction models into consideration before the start of the Model Construction task. Though the designer of design episode C did not apply the Decomposition (De) Macro Strategy, he claimed that he had considered in advance how to construct the model. All of the designers in the 4 design episodes, therefore, had considered the model construction before they used the CAID system. It is easy for the designer or computer operator, who has little experience of using CAID software, to encounter difficulties in Model Construction, and they may give up the original construction methods and look for other methods to accomplish the task.

In the application of Macro Strategies in Design Development, Top Down (Td) is also the major strategy in all of the 4 design episodes. Moreover, the record (protocol) is often scattered or interrupted. Judging from the Macro Strategy's point of view, the referring to macro Strategies is difficult to be considered as designer's thinking as a continuous or sequential behaviour model. The reason is that the designers have to construct some initial forms before they can start thinking about the design problem. However before they used the CAID system, the designers had discussed and refined the design through traditional drawing or 2D graphics in the early idea generation stage. The consideration on Design Development at the CAID stage is, therefore, not too heavy. The application of CAID tools can help designers refine their design in a more concrete manner. The CAID tool can therefore help designers verify the reliability and feasibility of the ideas generated in traditional drawing or 2D computer graphics. The pattern of Macro Strategy in the CAID environment, therefore, is fragmental, and not holistic.

Looking at the Top Down (Td) strategy applied in Model Construction, the conducting of Design Development can be looked at as a dependent Top Down model. That is to say, the Design Development task cannot proceed independently. Instead, it should accompany the Top Down (Td) Model Construction process in terms of evaluation and decision making, before completing the design problem. That means that the designer's thinking model was effected by the processes of CAID system to change into a Top Down model of Macro Strategies.

5.6 Summary

Through the verbal protocol experiment, some important conclusions have been obtained.

1. There are no big differences in the designer's thinking processes when using different CAID systems. Designers will follow the Top Down approach with the software in order to complete the design task.

2. When using 3D CAID software, it is vital for designers to deal with both Model Construction and Design Development tasks. They perform these tasks sequentially, one after the other or in parallel at the same time but in a cyclic manner. The speed and finish qualities for the Design Development task depend upon the quality and schedule of the Model Construction task.

3. In the CAID environment, an industrial designer, who is familiar with computer software, can perform the design activity in a smoother and faster way than an industrial designer working with a computer operator.

4. The experience a designer has in his or her professional discipline, is an important factor in effectively using the CAID environment, which is also true in traditional free hand drawings. The experienced designers' application frequency of Micro Strategies in Design Development and Model Construction is lower than that of junior designers. The reason is that the experienced designers have considered the design problem completely in the idea development stage before using the 3D CAID system. Consequently, the experienced designers do not have to dedicate so much energy to the 3D modelling process. Similarly, the experienced computer operators will consider more factors before they do the actual Model Construction

task. Therefore, they can handle the task better and encounter fewer difficulties. This is contrary to the application of traditional free hand drawings. The experienced designers will apply a wider variety of Micro Strategies more frequently when proceeding with design work manually (French, 1985; Mc Neill and Edmonds, 1994; Cross, et al., 1992).

5. In terms of Problem Domains, the experienced designers will consider more aspects of the design problem in the 3D CAID environment than the junior designers will. This is also the same situation when the traditional free hand drawing is used.

6. With present 3D CAID systems, it is not easy for designers to perform Design Development (Idea Refinement) and Model Construction in terms of quantity and quality of the task. The designer has to make more efforts in Model Construction than in Design Development, which means the former inhibits the latter. The current 3D CAID software can only be considered as a tool for transferring the 2D proposals into 3D models.

7. From the viewpoint of industrial designers, the degree of difficulty of design episodes can be determined by two types factors: one the design problem itself, and the other the complexity of the product form. In the protocol experiment, difficulties in product form complexity are not emphasised. However, the degree of difficulty may not be due to the complexity of product form, but weaknesses in the tools of the 3D software being used to complete the task. Four kinds of CAID software were used in the experiment, which are the most popular. However each of them has specific goal-oriented functions. For example, Alias and Rhino belong to surface structure group; Pro-E belongs to solid system group; and IDEAS belongs to both. If there is more than one 3D CAID package available in the

company or design house, the designer should choose 3D CAID software according to the characteristics of the product form, and the design objectives of the design problem before constructing models. However, which software is suitable for which design activity is not within the scope of this study. What the researcher is concerned with is the process of design development in the CAID system, but not the outcome of the design activity.

With these understandings of this experiment conducting comparing to others finds in Chapters 3 and 4, several recommendations will be obtained in Chapter 6. For refining the recommendations to a new CAID system, an evaluation will also be performed in the next study stage.

Chapter 6 General discussions, Recommendation and their Evaluation

In this study, the researcher has attempted to explore the influence CAID systems have had upon the designer's thinking process. Section 6.1 discusses how designers apply 3D software in the idea development stage at the present time.

6.1 The current application of CAID systems

According to the survey mentioned in Chapter 3, free hand drawings and 2D computer graphics are the major tools designers use to generate ideas. Though about 61% of the questionnaires show that 3D software is also used in the conceptual design stage, further examination (Section 3.4) verified that was only experimentation and not applied in practical design cases and designers would only try the tool when they had free time. Similarly, the survey of protocol records in Chapter 5 also shows that no design organisation wants to use 3D software as the major tool at the conceptual design stage, because the available 3D software is not suitable for designing in the early stages. Additionally, in Chapter 4, free hand drawing, 2D computer graphics, and 3D CAID software were examined in terms of idea generation. In this experiment, Designer C who used the 3D modelling software to generate ideas had lowest number of ideas. This was due to the complex operations of 3D modelling software. From the difficulties that Designer C encountered, the limits on designer's idea volume and creativity using 3D software in idea generation are clear.

Although the 3D-software tool has its limitations in idea generation, it is usually used to refine ideas in most design organisations (see section 3.5). In the idea refinement stage, designers perform the model construction and consider the design factors using 3D-modelling. The interaction between designer and computer in the model construction is therefore more intense than in the 2D-computer graphics stage of idea refinement. The purpose of the protocol experiment in Chapter 5 was therefore to explore the real situation of 3D software application in idea refining stage of design development.

In the current Computer Aided Industrial Design (CAID) environment, computer based free hand drawing remains one of the most important tools for idea generation and design development. 2D computer graphics are indispensable in the situation where precise dimensions and product form are required. 2D computer graphics also serve as an important basis at the beginning of 3D-model construction. Designers need to create their idea with 2D images, then based on the 2D images, generate the 3D model. This has been discussed and confirmed in Chapters 3, 4, and 5.

Though 3D software limits designer's traditional conceptual design, it does have potential in design development. For example, analysis and discussion with the designer using Microstation to perform the 3D model construction for the driving assistant device in Chapter 4, and the designers in design episode A refining the 3D model construction in Chapter 5, show that 3D modelling makes it possible for designers to consider more potential design solutions. However it can take more time and energy. For example, 3D software can make it more difficult for junior designers to conduct a design task and achieve the requirements of the design goal compared with traditional design tools.

In the experiments described in Chapter 3, no designer or design organisation applied design methods such as creative idea generation techniques, problem reduction, expansion, and digression (Chapter 2, p30), the permutation and arrangement of product function (Chapter 2, p31), to both idea generation and design development in a CAID environment. Though there may be some software that can integrate these techniques for idea development, no reliable system has been found to enable the designer to develop these ideas through the visualisation of the 3D model in a CAID based design development.

6.2 Designers' cognition and mental processing in a CAID environment

In terms of thinking processes, some research on cognition shows that some human thinking processes are like the information processing of computer programs (Lachman, Lachman and Butterfield, 1979). Meanwhile, most cognitive scholars claim that human being's cognition consists of the Top Down and Bottom Up processes of thinking (Burner and Postman, 1949). There are still some psychologists who claim parallel and serial processing take place within the human's mental processes (Eysenck, 1993). That is to say, a specific process will happen only when some process is over; but they will sometimes occur simultaneously. Eysenck (1993) pointed out that the frequency of parallel processing in a highly skilled person is higher than that of a person beginning to master a skill. Such processing was also found in Chapter 5. At the beginning of the Model Construction task, the Design Development task was also undertaken (See all of the Activity Charts in Chapter 5). Sometimes these two kinds of tasks are conducted separately. For example, when Model Construction is taking place, the Design Development task will cease, and vice versa. In addition, the frequency of parallel processing in the Model Construction and Design Development of the junior designers is much less than that of experienced designers. This is confirmed by the fact that junior designers spend less time on the Micro Strategies of Design Development. The research also shows that, under some certain circumstances, experienced designers will carefully consider the design problem and Model Construction methods before he or she enters the 3D CAID environment. Surprisingly, in this situation, the variety and frequency of Micro Strategies in Design Development and Model Construction is not very high, even though, the categories of Problem Domains are more extensive. This phenomenon indicates that in goal-oriented mental processing, though the frequency of thinking in experienced designers is high at the beginning, this kind of thinking process will decrease at a later stage. The reason for this is that the design factors not relevant to the design objectives will be ignored at an early stage. In this situation, it is more likely that parallel processing will occur, when considering each category of the Problem Domains and the Micro Strategies of Model Construction.

In terms of the impact of attention and memory upon the designer's thinking process, cognition research has indicated that on over-reliance of automatic processes will cause absent-mindedness (Shiffrin and Schneider, 1977). They consider that the function of memory is to store information and that there are many different types of information storage. Memory will be formed when short-term memory is turned into a long-term storage (Eysenck, 1977). In this study, the designer's attention is mainly focused on the graphics on the monitor screen. Their attention will be transformed by the way the designer perceives the stimulus and makes a decision. The designer's attention may switch from Model Construction to Design Development or vice versa. When the designer automatically tries a new model construction method but fails in the design task time after time, a short-term status of absent-mindedness will occur. However, over the long term the designers will began to realise that some methods applied will only be useful when revised. For example, the Op Macro Strategy in design episode A was adapted and applied fluently and was turned into a long-term memory. The designer in design episode A in Chapter 5, therefore, applied these methods previously found to construct the model in a later stage. It can therefore be inferred that the new method the designer figures out from the failed experiences will help the designer deals with similar difficulties encountered at a later stage in Model Construction. These techniques that are discovered could be acquired by an AI system for future use.

6.3 Suggestions for CAID systems

Figure 6.1 (on the next page) illustrates the design process in a CAID environment, where the design activity of the individual designer and different tools are illustrated. This diagram is a generic flow chart based upon the CAID flow chart of the design houses interviewed in the survey in Chapter 3 and on the protocol experiment in Chapter 5. It shows that free hand drawing and 2D computer graphics are more often applied at the conceptual and initial refining stage, while 3D software is frequently used at the final refining stage. This situation with regarding how designers in design the process use the design tools is the current one and is not ideal. According to the literature review and the survey in Chapter 3, the demand for continued improvement in 3D tools is evident. Based upon the characteristics of mental processing mentioned in section 6.1, the protocol study Figure 6.2 (on the next page) can be obtained. The serial processing is equivalent to the process of Model Construction in the CAID-3D environment. The situation when Model Construction and Design Development tasks proceed simultaneously is equivalent to the parallel processing. (In this context, parallel processing means the design activity of the designer using CAID-3D, not the processing of the computer's CPU.) In Macro Strategy application, two approaches, Top Down and Bottom Up are defined for designers, but Top Down is the only strategy possible using CAID systems. This is the biggest difference between designers and computers.

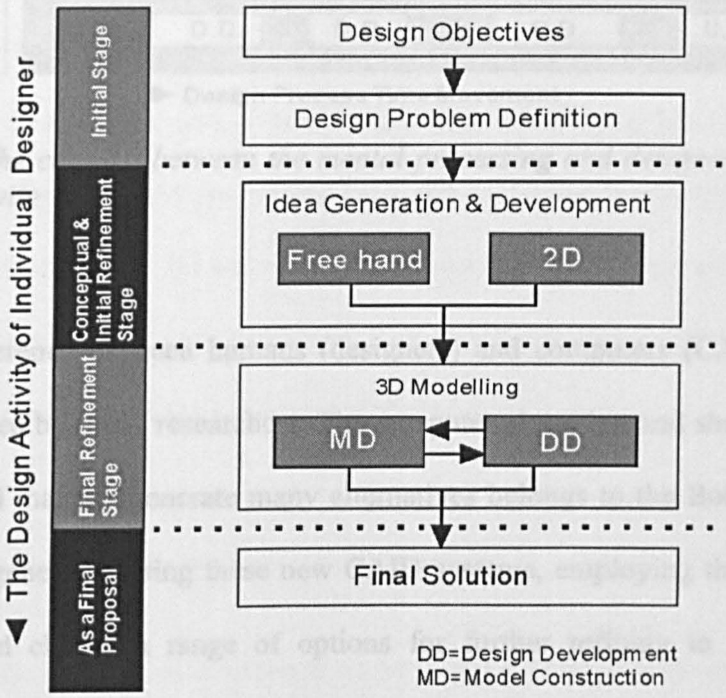

Figure 6.1: The process of the application of design tools and the design activity of individual designers

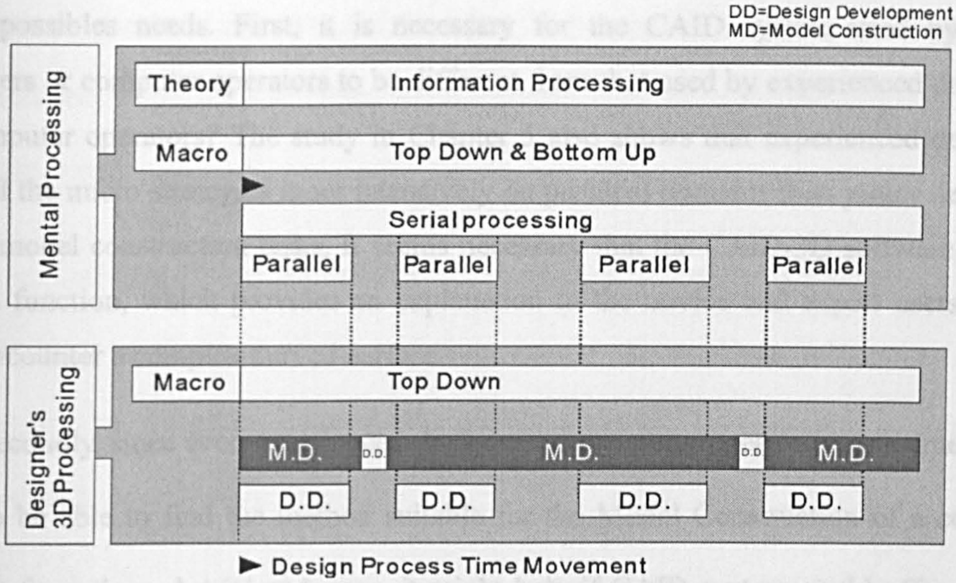

Figure 6.2: The contrast between the mental processing and designer's 3D processing in design activity

The difference between humans (designers) and computers (CAID systems) has been considered by many researchers. The computer algorithm and shape grammar (see P.68 and P.70) that can generate many alternatives belongs to the Bottom Up strategy. From output generated using these new CAID systems, employing these functions the designer could choose a range of options for further refining to meet the design objectives. This would be similar. For example, to the way sculptors can use Mutator software to create artistic works as described in Chapter 2.

It can, therefore, be inferred that, if current 3D-CAID tools can be equipped with a new algorithm system, the situation where designers can apply both Top Down and Bottom Up strategies in a CAID system can be carried out. Such a situation where Top Down and Bottom Up strategies could be applied interchangeably would better match the human information processing theories described by most cognition psychologists.

The analysis of the young designer of design episode A in Chapter 5 highlights two other possibles needs. First, it is necessary for the CAID system used by junior designers or computer operators to be different from that used by experienced designers or computer operators? The study in Chapter 5 also shows that experienced designers applied the micro strategies more intensively on problem domains than junior designers in 3D model construction tasks. It seems necessary that the CAID-3D software should offer a function, which provides an explanation to the novice and expert users, when they encounter a complex curved surface.

Secondly, since even experienced designers or computer operators sometimes seem only to be able to find the method suitable for the Model Construction of a complex product form through trial and error, it might help if CAID system could offer on-line suggestions to the users. At the present time, the user's operation steps and procedures in 2D software and some 3D software can be automatically recorded. Through the use of an Artificial Intelligent (AI) technique, it might be possible to offer helpful feedback based upon successful previous operations of designers.

6.4 The recommendations for future CAID system

Based on the discussions mentioned above, some recommendations for future CAID systems can be made and these are listed below.

1. Free hand drawing is still an important tool for an industrial designer in the idea development stage and should be used with in CAID (2D and 3D) systems.

2. There should be a single file format for all 3D CAID systems. A single file format will make file transfer much easier.

3. Since experienced and junior designers (computer operators) are different in terms of professional experiences and skills, future CAID systems should offer two

versions: one for the novice and the other for the expert, but be based on the same fundamental operation, graphics and commands. Designers should be able to switch easily between the two versions.

4. 3D modelling software needs to provide computer algorithm, shape grammar, or a database to generate alternative solutions from an initial 3D-model design solution. The solution generated from these systems can then be used as a reference for designer to solve design problems.

5. Future CAID systems should have a built in Artificial Intelligence (AI) to learn designers' modelling techniques and thus provide an automatic advice and support system.

6. CAID systems should also provide design method support such as problem reduction, problem expansion, and problem digression to help industrial designers explore possible solutions in the initial design stage.

6.5 Evaluation of final recommendations

In order to refine these recommendations for new CAID system, the researcher performed a survey to obtain professional designers and software engineers' opinions. The aim of this survey was to validate the results of the research. Experienced designers were invited to take part in this survey. As they had been designers for a long time, it was felt their opinions would be helpful to refine the recommendations.

6.5.1 The design of the questionnaire and the weighting of the responses

A questionnaire survey was designed to evaluate and refine the recommendations. The contents of the questionnaire can be seen in Appendix L. The questions were specially targeted to evaluate the recommendations in section 6.3 and the results of general discussion in section 6.2.

For each question in the questionnaire, a 7-point scale from agreement to disagreement was employed (see Figure 6.3). The subjects had to specify their choice and a space was also provided to express their opinions. On the 7-point scale a score from 1 to 3 was used to indicate the level of "agreement" to the question, and a score from –1 to –3 was used to indicate the level of "disagreement". If the subjects neither "agreed" nor "disagreed", they could select "0". The researcher could then infer the overall agreement to questions by calculating the total points for each question. The answers of subject (who were invited to answer the questionnaire) also can be seen in Appendix M. As 8 people took part in the survey the highest and lowest scores possible are 24 and –24 respectively.

	-3	-2	-1	0	1	2	3	
NO	☐	☐	☐	☐	☐	☐	☐	YES

Your Suggestions: ____

____

____

Figure 6.3: A sample of a 7-point scale to a question

6.5.2 The answers to the questionnaire from the subjects

The questionnaire was completed by seven experienced designers and one software-engineer. Their professional experience is shown in Table 6.1. Four of the designers and one software engineer have more than 7 years of experience. Although only a small subject sample was taken in this survey, their answers to these questions are useful and can be used as a basic evaluation of the recommendations of the research, due to their experiences of design. The 3D software packages that they are familiar with or design with is shown in Table 6.2. The total range of computer software used by them includes Alias, Auto-CAD, Cadkey, Ideas, Microstation, Pro-E, Solid edge, Solid work, and Vellum Solid. The most popular computer software used by them is Ideas.

Table 6.1 The experience of the experts in the questionnaire survey

Experiences / Professions	1-3 years	4 - 6 years	More than 7 years
Design experts	1	2	4
Chief software engineer	0	0	1

Table 6.2 The distribution of the 3D software packages used by the designers

Computer software	Auto-CAD	Ideas	Pro-E	Solid work	Solid Edge	Alias	Cadkey	Microst -ation	Vellum Solid
Vol.	2	3	2	1	1	1	1	2	1

The answers from all the subjects are now below in the order they are asked.

Question 1. Do you agree that free hand drawing is still an important tool for an industrial designer in idea development? The answers to this question were strong agreement with a score, 23 points. The comments from these subjects also indicated that 2D and 3D computer software needs have computer-based free hand drawing to facilities conduct idea generation.

Question 2. Do you agree that free hand drawing is more productive in output of idea generation compared to using 2D-computer graphics software using? Most of the subjects agreed with this point with a score of 17 points with no negative opinions. The designers stated that free hand drawing is the most convenient tool to generate and to express their ideas. One of the experienced designers (subject 5 scored "0") thought that free hand drawing and computer software should be used equally for idea generation. This point indicates that a combination of free hand drawing, 2D, and 3D-computer software is a better solution for industrial designer in conducting idea generation and refinement.

This point supports the findings of the studies in Chapters 3 and 4. Additionally, free hand drawing is not only important in traditional design processes, but is also important for designers in a computer-based environment.

Question 3. Do you agree that the use of 2D-computer graphics software is more suitable for the initial idea refining stage in industrial design? Most of the answers did not strongly agree with this question scoring only 3. Subject 1 agreed with this statement, but he also pointed out that it could depend on how familiar designers are with the 2D-computer software. Subject 3 asserted that it is much easier to go to use 3D graphics of either solid or surface modelling, after initial conceptual design on paper. Subject 7 also stated that he would like to skip 2D graphics and go straight to 3D modelling. Subject 6 considered that the combination of free hand drawing, 2D CAD, and 3D CAD was better system for designers. However, he stated that 2D computer graphics is only a follow up stage after the idea generation stage, and it can be skipped before proceeding to the 3D modelling stage. The designer decides which tool is according to the requirements of design projects and their familiarity with the tools.

2D-computer software is therefore not considered important in idea refinement by most designers in this survey, but it is still an important tool in 3D-model construction before designer's work on a 3D model for their ideas. Trying to skip the 2D computer graphics to conduct the 3D-model construction directly would be a valuable area for the future research.

Question 4. Do you agree that 3D software is not suitable for idea generation? The over all score indicated slight agreement to this statement with a score of 6. 3 subjects agreed with this question, but one subject did not. The other 4 subjects' all scored "0" indicating neither agreement nor disagreement. Subject 3 explained that 3D software was ideal for secondary conceptual design generation, as it is then much easier to manipulate and reiterate your thoughts. Subject 8 thought that 3D modelling takes too much time is therefore a barrier for idea generation. Subject 2, a software-engineer, was not sure. If it is used in the proper way then yes it is suitable but if you use it to create fully detailed ideas in 3D it can be unsuitable. Subject 7 expressed that 3D modelling takes longer to model ideas, but sometimes it can communicate ideas better, and thus shorten the evaluation process.

3D modelling is not considered suitable for idea generation at present. In the future, however, the improved 3D modelling software may be an important tool in performing idea generation without taking too much time due to easier methods to model designers' ideas.

Question 5. Do you agree that 3D modelling software is often applied in the final refining stage in industrial design? The score of 13 indicates agreement to this question.

Most of the subjects agree that 3D modelling is often used at the final refining stage. Even subject 2, the software-engineer, agreed to this viewpoint. Subject 6, however, disagreed with this question due to his own skills with 3D modelling software. He was familiar with three kinds of software packages, Ideas, Microstation, and Solid Edge. That is a specific of a designer using more than one 3D software package to develop his ideas; at the initial idea refinement stage and not just at the final refinement stage.

Although subject 6's statement indicates disagreement to this question, most designers thought that the 3D modelling software package is must often used in the final refinement stage in industrial design. With the result of this question and the answers to question 4 a simple conclusion is that the 3D modelling software is not only un-suitable for idea generation, but also is takes too much time and effort for designer in the initial refinement of their rough ideas. Based on this result, the present 3D modelling software packages need to be improved to so that it is an easier operation to construct models.

Question 6. Do you agree that when an industrial designer uses 3D modelling software, two activities, model construction and design development (refinement) take place? To this question the positive answers were 16 points. Subject 1 thought that if the designer was good at using 3D-computer software, he or she develops the detail of the product form more deeply. Subject 2 expressed that 3D model construction will be easier, if the design can be refined beforehand. Comparing these answers to the results in the survey of CAID system used in Taiwan in Chapter 3, they also support the idea that experienced and junior designers conduct 3D-model construction along with the design refinement.

Question 7. If free hand drawing can be combined with 2D computer graphics and

3D modelling software into a CAID system, do you think that it will help industrial designers to deal with the design problems? The answers to this question were positive with a score of 23 points. Only subject 3 had a different viewpoint claming it is faster for a group of people to get around a piece of paper. This subject was concerned with technology-based problems on a computer, but overall he agreed with this question. This indicates that such a new CAID system would be ideal for most designers supporting this study's recommendation.

Question 8. Do you agree that there should be a single common file format for all 3D CAID systems? The total score for this question was 19. All of the subjects who were designers agreed with this point, but subject 2, the software-engineer, had a different opinion claming it would be nearly impossible because of commercial considering. All systems have many years of development and a standard format would be good for one but not necessarily another.

Although the development of a single common file, might not be important from the manufacturer's point of view designers would welcome this development to remove the barriers of different file format transformations. In order to get rid of these barriers in 3D modelling software a file standard would be organised and updated by an international organisation. The 3D software manufacturers would then need to modify accordingly for file transfer.

Question 9. Do you agree that because experienced and junior designers (computer operators) are different in terms of professional experience and skills, future CAID systems should offer two versions: one for the novice and the other for the expert, but be based on the same fundamental operation, graphics and commands? The score was 2 so there was only a slight agreement. Most of the subjects were concerned that this CAID system would be very expensive and take more time to learn, but they thought this CAID system would be a suitable tool for both the novice and the expert.

So, this type of new CAID system should not be too expensive, and be simplified in operation so that it is easy to learn.

Question 10. Do you agree that the 3D modelling software needs to work with an algorithm system to generate alternative solutions for the industrial designers as reference for 3D models in design problems? There was agreement to this question with a score of 9. Subject 1 disagreed with this point claming that this CAID system would remove designers' creativity. Subject 6 thought this CAID system would be needed when the designer is weak or inexperienced.

Normally, industrial designers should conduct design tasks with their imagination and creativity, but sometimes they might take a design reference from this type of CAID system to examine other possibilities. Industrial designers would then be able to conduct both Top Down (the present CAID system) and Bottom Up (this new CAID system) processes in design projects.

Question 11. Do you agree that future CAID systems should have a built in Artificial Intelligence (AI) to learn designers' modelling techniques and thus provide an automatic advice and support system? The score of 13 points indicates agreement to this question. The subjects agreed with this question and thought that this CAID system would help designers conduct their designs faster and in a more efficient way, especially for performing routine designs.

Question 12. Do you agree that CAID systems should also provide design methods support such as problem reduction, problem expansion, and problem digression, to help industrial designers to explore possible solutions in the initial design stage? The score of 5 points indicates some agreement to this question. Subject 6 disagreed however claming that because design can be very different it should not be tackled by a formula. As this would be dangerous and potentially restrict creativity. Subject 1 and 3 were not sure this type of CAID system would either help or stop designers' creativity in the idea generation stage.

However, this CAID system might be useful to analyse or de-construct design problems using a particular design method. For example, the image board is always used by industrial designers to explore the form features of products that may be applied in a CAID system. The designers should know about design methods, and could then select an appropriate method to conduct the design, according to the requirements of the design objectives.

6.5.3 The discussion of the answers for the questionnaire

After carefully checking the answer to the questionnaire, the research has ascertained that the more experience the designers have, the more they trust themselves with their skills and knowledge. Subjective 6 had worked in the industrial design field for more than 7 years and was familiar with 3D-modelling software, Ideas, Microstation, and Solid Edge. He used the 3D-modelling software to create his ideas at the initial idea design that is very different from the other subjects. However a more negative attitude to the new methods proposed for 3D modelling software such as, computer algorithms and design methods. He wondered whether the proposed functions and methods would help designers to conduct design tasks without negative effect on designers' thinking and creativity. However, the researchers found that the majority of designers in this survey agreed that these new functions and methods would be useful to junior designers and sometimes even to the experienced designers.

The new functions and methods proposed seem to be accepted more by those designers whose experiences was less than 6 years in this survey. This indicates that junior designers would welcome a different CAID system that could assist them with generating references or suggestions for their design tasks.

Subject 2, a software-engineer was very positive about the proposed new functions and methods. He disagreed that the 3D file formats could become a single common one, due to the fact that each 3D software took many years to develop by different companies. Even so, to satisfy the designers' needs in conducting design tasks format standards should converge to a compatible file.

The recommendations for new CAID systems resulting from this study are therefore supported by most of the designers' in this survey. More detailed conclusions and some suggestions for future research in the CAID systems will be discussed in the Chapter 7.

Chapter 7 Conclusions and future research suggestions

7.1 The final conclusions for future CAID system

Based on the general discussions and the evaluation of recommendations in Chapter 6, several final conclusions can be proposed and these are listed below.

1) 2D and 3D software needs computer-based free hand drawing to facilities for idea generation.

   The traditional free hand drawing provides more freedom and is more efficient than 2D and 3D computer software, according to the experiment held in Chapter 4. In Chapter 6, all of the experienced designers agreed that free hand drawing should be built into 2D and 3D computer software to help designers perform the design more. The designers who answered the questionnaire in chapter 6, also agreed that using free hand drawing is more productive in idea generation compared to 2D-computer graphics software. The designers using this type of new CAID system could obtain all the benefits both free hand drawing and computer-based system.

2) 3D-model construction in a new CAID system should not require earlier 2D computer graphics.

   2D computer graphics is a follow up stage after the idea generation prior to 3D model construction task this was stated in Chapter 6 by the experienced designers all had similar opinions. If designers could do the 3D-model construction directly without the need to create 2D graphics, the time required for design development would be less. The question is how 3D modelling software should be designed and with what kind of interface to achieve this aim? Also will designers do better design and get better quality design solutions without using 2D computer graphics? Future research would be required to determine the answers to these questions, which could be an important improvement.

3) 3D modelling software should be simplified the operation procedure of model construction is easier and takes less time.

In 3D-model construction, industrial designers need to perform the refining task of Design Development while using 3D modelling software. Industrial designers, therefore, have to ensure the quality and speed of these two kinds of tasks. This means that if 3D model construction take designers a long time, then the speed and quality of design refinement is also decreased. Additionally, using 3D modelling software as an idea generation tool is more difficult than using free hand drawing and it is takes too much time to model an idea. In question 4 of section 6.5.2, the experienced designers agreed with this viewpoint and also mentioned that as 3D modelling takes so much time it is a barrier to idea generation. Both design refinement and generation would be helped by making model construction easier.

4) 3D modelling software have a single common file format.

All of experienced designers, except the software engineer, agreed with this point in the questionnaire survey in Chapter 6. Although software manufacturers spend a lot of time and money on their own file format and will be reluctant to change it, a single file format always is important requirement for design world. The software manufacturers should try to reduce the problems with file format transferring and updating their old formats.

5) Future CAID systems should offer two versions in one package: one for the novice and another for the experts that are inexpensive and have a user-friendly interface.

   Due to the different levels of experience in design and 3D-model construction between experienced and junior designers, their design tools should also be different. When junior designers encounter a complex product form and cannot resolve it, they should be provided with suggestions from the novice version of 3D-CAID system to solve complex form problems. Even the experienced designers might sometimes need this function too. The two versions of the 3D-CAID system should be based on the same fundamental operation, graphics and commands. In the survey in Chapter 6, the experienced designers' opinions to this viewpoint were only in slight agreement, as they thought this type of new CAID system would not be easy to learn and would not be economic for a company. However, if this type of CAID system could overcome these problems, it would be an ideal for most designers.

6) Future CAID systems should have a built in Artificial Intelligence (AI) to learn designers' modelling techniques and thus provide an automatic advice and support system.

   The CAID-3D system should be intelligent enough to turn the operator's successful procedures in model construction into suggestions for the novice. In this way, the sense of frustration and the time for Model Construction could be greatly reduced. In the survey in Chapter 6 this recommendation was supported by experienced designers who thought that this new CAID system would help designers do their designs, too.

7) CAID systems should provide design methods support such as problem reduction, problem expansion, and problem digression, to help industrial designers explore possible solutions in the initial design stage.

   This point was supported by the experienced designers in the survey in Chapter 6. The functions of CAID system would provide designers with another tool to explore possible solutions or give designers a more profound understanding of design problems. However, the aims of this CAID system would be only to give a suggestion or a method for the designer to conduct design analysis and design problem deconstruction.

8) The 3D modelling software needs to work with an algorithm system to generate alternative solutions for the industrial designers as a reference for 3D models in design problems.

   On this point, most of experienced designers thought that this would remove designers' creativity. If the designers were inexperienced, the new system would help them with some ideas of 3D model. They could then develop solutions from the 3D models proposed by the new CAID systems.

7.2 The limitations and constraints of the research

This research focuses on the observation and analysis of how designers apply CAID system to perform their design activities. The functions and characteristics of CAID 2D and 3D systems are not specially explored. The reason for this is that the researcher wanted to explore the software representative in the design field, rather than some specific systems. In terms of mental processing, the researcher examined only a few theories about cognition to infer how designers' mental processing works in a CAID environment. It is not based upon the whole spectrum of cognition theories. What the researcher wanted to investigate is the cognitive behaviour of designers in the CAID environment.

Mainly based on what the designer says and the graphics output on the screen, the verbal protocol test was encoded and further analysed to reach the goal of this research. The silent parts or segments for which it was not possible to code should be clarified with a more suitable method in the future. In addition, how thinking aloud affects the subject's behaviour is not yet known. These are some of the limitations of the research.

The designers and computer operators of the design houses in the survey and protocol experiment were chosen according to the criteria which were help to research quality. Due to the limits of time, manpower and cost, the number of subjects is limited. Just a small number of designers and computer operators were interviewed or recorded in this research.

In terms of the specifications and capacity of the hardware in the protocol experiment, there were no specific criteria. Hardware consisted of Pentium III-133 CPU and 8MB-video card can offer the basic functions. The impact the computer hardware has on the real CAID environment is not covered in this research.

Also, the research did not focus on what kinds of commands and model construction methods the designers use in dealing with the CAID systems. The detailed process and the relationship between the designer's behaviour and the interface design of the CAID system go beyond this research.

Achievement of the research objectives

Objective 1: To review and understand how industrial designers apply CAD systems in design activities, especially in idea development?

This objective was explored in Section 3.3 and Section 3.4 with a questionnaire survey and the follow-up face-to-face interview.

Objective 2: To compare and contrast different CAID systems.

This objective was achieved in Section 3.2 and also in Section 3.3 and Section 3.4. In section 3.2 the researcher identified that the most popular four 3D-medelling software are Alias, Ideas, Pro-engineer, and Rhino. The use of different CAID systems was subsequently explored in Section 3.3 and Section 3.4.

Objective 3: To verify the difference and utility in using different tools, i.e. free hand drawing, 2D-Computer drawing and 3D computer modelling.

This objective was achieved in Section 3.3 and Section 3.4. In section 3.4, how the design process of each design organisation was influenced by the different tools used was examined. These design processes can be seen in

Figure 3.38, Figure 3.40, Figure 3.41, and Figure 3.42.

Objective 4: To develop an experiment to identify the discrepancies of idea development between using traditional tools and the modern CAID systems based techniques.

This objective was achieved by the experiment described in Chapter 4. The test was performed using three different tools for idea generation. The tools were free hand drawing, 2D-computer graphic, and 3D-modelling computer software.

Objective 5: To discuss the designer's way of thinking in using CAID systems for idea development

This objective was achieved in Section 5.4 and Section 5.5 in which four design episodes performed by four design teams using the CAID systems were examined.

7.3 Suggestions for future research

The results of this research show that there are many problems to be explored in the future. Some suggestions regarding the issues of the further study of CAID are listed below:

(1) A differential study of the efficiency of different 3D software.

(2) A differential study on the using between the traditional free hand drawing and a

computer-based free hand for product design.

(3) A study of the possibility for designers works on a design project without 2D computer graphics in 3D modelling software using.

(4) A study of the development of novice versions and expert versions within the same 3D CAID system.

(5) A differential study of junior and experienced designers using the same 3D software.

(6) A differential study on the performance of design activity by using different platforms of hardware.

(7) A study on CAID systems that can assist the designers at all stages of the design process.

(8) A study of an intelligent CAID system that integrates design methods and skills can be approached in several ways. For example, is it possible to apply a computer algorithm or shape grammar to the design activity in industrial design? Is it possible for us to use some sort of database to automatically generate alternative designs through some inference rules? Such CAID systems should take human being's cognition into consideration.

A CAID system that fits the designer's mental processing is one of the biggest challenges for the future.

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Appendix A: The Questionnaires of surveying the CAID process

1.What are the major products you design?

☐Computer ☐Communication ☐Consumer products

☐Medical equipment ☐Optical ☐Weapons and space equipment

☐Transportation ☐fitness & amusement ☐Toys

☐Furniture ☐Clocks and watches ☐Jewelry

☐Fashion & textile ☐Lighting ☐Hand tools & equipment

☐Hardware ☐Other________

2.Please specify the professional background of your designers.

☐Design planning ☐Design management ☐Design research

☐Design strategy ☐Design integration ☐Industrial design

☐Mechanical design ☐Graphic design ☐Color planning

☐Specialist of CAD ☐Model making ☐Other________

3.What kinds of design service do you offer?

major items of design services:

☐Graphics ☐Industrial design ☐Mechanical design

☐Color planning ☐Model making ☐Design research

☐Market investigation ☐Testing & evaluation ☐Other________

minor items of design services:

☐Graphics ☐Industrial design ☐Mechanical design

☐Color planning ☐Model making ☐Design research

☐Market investigation ☐Testing & evaluation ☐Other________

4.What kinds of systems do you use in each stage of design development?

Stages Systems	Conceptual	Idea test	Idea refine	Ideas evaluation	Rendering	Engineering drawing
Hand draft & sketch						
2D computer software						
3D computer software						
Other____________						

5.Which system do you use most frequently in the conceptual design phase?

☐**Hand draft & sketch**

☐**2D computer software**

☐Auto-CAD ☐Microstation ☐MicroCAD ☐Smart-CAD ☐Other_____

3D computer software

☐The AMD of Auto-CAD ☐Microstation ☐3D studio ☐Ideas

☐Smart-CAD ☐Catia ☐Alias ☐Solidedge

☐Pro-Engineer ☐Solidwork ☐CADKey ☐VR

☐Rhinoceros ☐Superscape ☐Sense 8 ☐other_______

6.Why do you use those computer software?

☐**2D computer software**

☐Friendly interface ☐Powerful function ☐Easier file transformation

☐Speedy calculation ☐Small file capacity ☐Ease construction

☐Economy ☐Flexibility ☐Other_______

☐**3D computer software**

☐Friendly interface ☐Powerful function ☐Easier file transformation

☐Speedy calculation ☐Small file capacity ☐Ease construction

☐Economy ☐Flexibility ☐Other_______

☐**Other**

☐Friendly interface ☐Powerful function ☐Easier file transformation

☐Speedy calculation ☐Small file capacity ☐Ease construction

☐Economy ☐Flexibility ☐Other_______

7.What kinds of tasks will you proceed idea generation by computer systems?

☐**2D computer software**

☐Styling ☐Graphic ☐Form study ☐Visual media

☐Letter form ☐Drafting ☐Logos ☐Mechanical Design

☐Test & evaluation ☐Other_______

☐**3D computer software**

☐Styling ☐Graphic ☐Form study ☐Visual media

☐Letter form ☐Drafting ☐Logos ☐Mechanical Design

☐Test & evaluation ☐Other_______

☐**Other**

☐Styling ☐Graphic ☐Form study ☐Visual media

☐Letter form ☐Drafting ☐Logos ☐Mechanical Design

☐Test & evaluation ☐Other________

8.At the beginning of conceptual design phase, which CAD operations do you undertake to design problems?

☐1.Use 2D graphic software to create images directly on the computer.

☐2.Use a free hand digital pad to draw sketches in 2D computer software.

☐3.Use a 3D software to create a 3d image of ideas with PC or problems.

☐4.Use some cell library of database to generate reference ideas for design problems.

☐5.Use solid models to search for the solution to design problems.

☐6.Other:(please brief your approaches.)____

____

9.In the conceptual design phase, how do you connect 2D sketches into 3D images?

☐1.Use the 2D dimensions to construct 3D image.

☐2.Scan the 2D sketches and trace them.

☐3.Use the 3D software directly to create ideas of solution to design problems.

☐4.Sketches directly to generate 3D image in computer.

Please list the software name:____

5.Other:____

____

10.What impact will CAD system cast upon the designers?

Negative less **1 2 3 4 5** more

☐1.Obstruction of idea generation ☐☐☐☐☐

☐2.Less creativity ☐☐☐☐☐

☐3.Fake-image of solutions ☐☐☐☐☐

☐4.Time consuming in learning computer software ☐☐☐☐☐

☐5.Difficulty in trouble shooting of computer systems ☐☐☐☐☐

Positive less **1 2 3 4 5** more

☐1.Increase of number and variety of solution ideas ☐☐☐☐☐

☐2.More creativity ☐☐☐☐☐

☐3.Seeming reality of solution ideas ☐☐☐☐☐

☐4.Acceleration of design development ☐☐☐☐☐

☐5.Decrease of errors ☐☐☐☐☐

☐6.Better design quality ☐☐☐☐☐

11.What other software do you use except the 2D & 3Dsoftware? Also how?

☐No ☐Yes. Please list them:__________________________________

____

____

12.What CAM systems do you use to build physical models?

☐CNC machine for____

☐Stereo lithography for_____________________________________

☐Other:____

Appendix B: The raw material of questionnaire

	Subject 01 **Design department**	**Subject 02** **Design department**	**Subject 03** **Design department**
1.	Optical	Transportation	Computers , Communication
2.	DM = 2 , ID = 7 , GD =4	DP = 20 ,DM = 10 , DR = 20 ,DS = 5 , ID = 6 ,MD = 70 , CP = 3 , CAD & M =10 MM = 5	DM = 1 , DI = 18 , ID = 5 ,MD = 72 , GD = 6
3.	Major = ID Minor = G	Major =ID , MD , CP , MM , DR , MI , T&E Minor = G	Major =G ,I D,M ,DR , T&E Minor = CP , MM , MI
4.	HDS = Conceptual . Rendering 2D = Engineering drawing 3D = Idea test , Idea refine , Idea evaluation , Rendering	HDS = Conceptual , Idea test , Idea refine , Idea evaluation , Rendering 2D = Idea test ,Rendering 3D = Conceptual , Idea test , Idea refine , Idea evaluation , Rendering , Engineering drawing	HDS = Conceptual , 2D = Idea test ,Eng. Dwg., 3D = Conceptual , Idea evaluate , Engineering drawing
5.	HDS 2D = * 3D = PRO-E	HDS 2D = Auto-CAD , Microstation 3D = Alias , Rhinoceros	HDS 2D = Auto-CAD 3D = Alias , PRO - E
6.	2D = * 3D = PF , SC , EC Other = *	2D = PF , EC , F 3D = PF , ET ,EC , F Other = *	2D = FI , ET , SC , EC , E 3D = FI , PF , EC , F Other = *
7.	2D = G , Draft 3D = S , FS Other = *	2D = S , G , VM , LF , DR , LOGO 3D = S , FS , VM , LF , DR , LOGO , MD , T&E Other = *	2D = S , G , DRFT , MD 3D = LF , MD Other = *
8.	3	1 , 2 , 3 , 5	1 , 3
9.	1	1 , 2 , 3	3
10.	N : * P : * , * , 4 , 4 , 0 , *, *	N : 1 , 2 , 3 , 5 , 3 P : 5 , 4 , 5 , 4 , 5 , 5	N : 5 , 4 , 4 , 2 , * P : 5 , * , 5 , 5 , 5
11.	*	*	*
12.	*	CNC , SL , VACOM	*

	Subject 04 Design-house	Subject 05 Design-house	Subject 06 Design department
1.	Computers , Communication , Consumer Products , Fitness & amusement	Consumer Products , Transportation , Hand tools & Equipment	Computers , Communication Consumer Products
2.	DP = 1 , DM = 1 , ID = 3 , MD = 2 GD = 1 , CAD = 1	ID = 3 , MD = 4 , MM = 1	DM = 1 , DR = 3 , ID = 6 ,MD = 3 , CP = 5
3.	Major = ID , MD , CP , DR Minor = G	Major = ID , MD , MM Minor = G , CP	Major = ID , MD , CP Minor = G , DR , T & E
4.	HDS = Conceptual , Idea test , Idea refine , Ideas evaluate 2D = Idea refine, Ideas evaluate , Rendering , Engineering drawing 3D = Idea refine ,Idea evaluation , Rendering , Engineering drawing	HDS = Conceptual 2D = Idea test 3D = Conceptual , Idea test , Idea refine , Idea evaluation , Rendering , Engineering drawing	HDS = Conceptual , 2D = Idea test ,Eng. drw. 3D = Conceptual , Idea refine , Idea valuation ,Render , Engineering drawing
5.	HDS 2D = Auto-CAD , Coreldraw 3D = *	HDS 2D = Auto-CAD 3D = PRO-E	HDS 2D = Auto-CAD 3D = Alias , PRO - E
6.	2D = EI , SC , E , F 3D = PF , SC , EC , F Other = *	2D = * 3D = PF , F Other = *	2D = * 3D = PF , F Other = *
7.	2D = S , G , FS , VM , Draft , L , MD 3D = S Other = *	2D = Other (IG) 3D = S Other = *	2D = T & E 3D = S , VM , MD , T & E Other = *
8.	1	1 , 3 , 5	1 , 3 , 5
9.	1 , 2 , 3	3	1 , 2 , 3
10.	N : 3 , 1 , 5 , 5 , 3 P : 5 , 4 , 5 , 5 , 5 , 5	N : 2 , 1 , 4 , 3 , 1 P : 4 , 3 , 4 , 4 , 4 , 5	N : * P : 4 , 5 , 4 , 3 , 3 , 4
11.	*	*	YES(Coreldraw , Photoshop)
12.	CNC	CNC , SL , HM	CNC

	Subject 07 Design department	Subject 08 Design-house	Subject 09 Design-house
1.	Computers , Consumer Products , Fitness & amusement , Hand tools & Equipment	Computers ,Consumer Products , Communications	Computers , Consumer Products , Medical equipment , Toys , Transportation
2.	DM = 1 , ID = 1 , MD = 1 , GD = 1 , CAD = 2	ID = 3	ID = 8
3.	Major = G ,ID , MD , CP Minor = MM , DR	Major = ID Minor = G	Major = G , ID , DR Minor = MM , MI
4.	HDS = Conceptual 2D = Conceptual , Idea test , Idea refine,Ideas eval., Rendering , Engineering drawing 3D = Conceptual , Idea test , Idea refine , Idea eval. , Rendering , Engineering drawing	HDS = Conceptual , Idea test 2D = Engineering drawing 3D = Conceptual , Idea refine , Idea evaluation , Rendering , Engineering drawing	HDS = Conceptual , 2D = Idea test , Idea refine , Ideas evaluate , Render , Engineering drawing 3D = Conceptual , Idea test , Idea refine , Idea eval. , Rendering,
5.	HDS 2D = Coreldraw 3D = Alias , PRO-E	HDS 2D = Auto-CAD 3D = Alias	HDS 2D = Auto-CAD , Microstation 3D = Microstation , PRO - E
6.	2D = FI , PF , ET , SC , EC , E 3D = FI , PF , ET , SC , EC Other = *	2D = * 3D = * Other = *	2D = FI , EC , Other(Popular) 3D = FI , EC Other = *
7.	2D = S , G . VM 3D = S , FS , VM , MD , T & E Other = *	2D = G , VM , Draft 3D = S , FS Other = *	2D = S , G . VM ,Draft , L 3D = S , VM , MD , T & E Other = *
8.	1 , 3	3	1 , 3 , 5
9.	1	2	3
10.	N : 1 , 1 , 5 , 4 , 4 P : 3 , 3 , 5 , 5 , 3 , 5	N : 1 , 1 , 4 , 5 , 3 P : 3 , 5 , 5 , 5 , 4 , 5	N : 1 , 1 , 4 , 5 , 3 P : 3 , 3 , 5 , 4 , 4 , 4
11.	YES (Direct 5.0)	*	YES(Humanfactor)
12.	CNC , SL	CNC	SL

Subject 10 Design-house	Subject 11 Design-house	Subject 12 Design-house
1. Computers , Consumer Products , Fitness & amusement , Medical equipment , Optical DM = 2 , DR = 1 , 2. DI = 2 , ID = 5 , MD = 2 3. Major = ID , MD , CP , DR Minor = G , MM 4. HDS = Conceptual , Idea test , Idea refine , Rendering , Ideas evaluation 2D = Engineering drawing 3D = Conceptual , Idea refine , Idea evaluation , 5. Engineering drawing HDS 6. 2D = Auto-CAD 3D = Alias , Ideas 2D = FI , PF , EC , E 3D = FI , PF , EC 7. Other = * 2D = G , Draft , MD 3D = S , FS , MD 8. Other = * 9. 3 10. 2 , 3 11. N : 1 , 1 , * , * , * P : 4 , * , 4 , 5 , 5 , * 12. * CNC	1. Computers ,Consumer Products 2. DP = 1 , DM = 1 , ID = 3 , MD = 5 3. Major = ID , MD , T&E Minor = * 4. HDS = Conceptual , Idea refine 2D = Idea Test , Rendering , Engineering drawing 3D = Idea refine , Idea evaluation, Rendering , Engineering drawing 5. HDS 2D = Auto-CAD 3D = PRO-E 6. 2D = FI , EC , E 3D = FI , PF , EC Other = * 7. 2D = S , D , MD 3D = S , MD Other = * 8. 1 , 3 9. 3 10 N : 2 , 1 , 3 , 4 , 1 P : 2 , 2 , 5 , 5 , 3 , 4 11 * 12 CNC	1. Computers , Consumer Products , Communications , 2. ID = 8 , MD = 2 3. Major = MI , ID , MD , DR Minor = G 4. HDS = Conceptual , Idea test 2D = Engineering drawing 3D = Conceptual , Idea refine , Idea evaluation , 5. Render, Engineering drawing HDS 2D = Coreldraw , Photoshop 6. 3D = Alias, Microstation, Pro-E, Rhinoceros 2D = FI , EC , E 3D = FI , PF , EFT , SC 7. Other = * 2D = S , G , VM , D , MD 8. 3D = S , FS , MD , D Other = * 9. 1 , 3 10 1 , 2 11 N : 2 , 3 , 3 , 3 , 3 P : 3 , 3 , 5 , 5 , 5 , 5 12 * CNC

	Subject 13 Design department	Subject 14 Design department	Subject 15 Design-house
1.	Computers , Consumer Products , Fitness & amusement , Communications	Consumer Products , Optical , Communications ,	Medical equipment
2.	DM = 1 , ID = 3 , MD = 2	DM = 2 , ID = 5 , MD = 10 , GD = 1	DM = 1 , DR = 1 , ID = 3 , MD = 3 GD = 1
3.	Major = ID , MD Minor = G	Major = ID , MD Minor = G	Major = ID , MD Minor = G , MD
4.	HDS = Conceptual , Idea test 2D = Idea test , Engr. drw 3D = Idea test , Idea refine , Idea evaluation ,Rend. Engineering drawing	HDS = Conceptual 2D = Conceptual , Idea refine , Rendering , 3D = Conceptual , Idea test , Idea refine , Idea evaluation , Rendering , Engineering drawing	HDS = Conceptual 2D = Idea refine , Engineering drawing 3D = Idea Test , Idea refine , Idea evaluation ,Render , Engineering drawing
5.	HDS 2D = Coreldraw 3D = Pro-E	HDS 2D = Auto-CAD , Coreldraw 3D = Alias, Pro-E	HDS 2D = * 3D = Alias
6.	2D = FI , EC , E 3D = FI , PF , EFT , EC , F Other = *	2D = FI , EC 3D = FI , PF , EF , EC , F Other = *	2D = FI , PF 3D = FI , PF , EC Other = *
7.	2D = S , G , VM , D , MD 3D = S , FS ,VM , MD , D Other = *	2D = S , G , D , MD 3D = S , FS , D , MD Other = *	2D = S 3D = S , FS Other =
8.	1 , 3	1 ,2 , 3	2
9.	1 , 2	1 , 2	2
10.	N : 1 , 1 , 2 , 3 , 3 P : 3 , 3 , 3 , 5 , 4 , 5	N : 1 , 1 , 4 , 4 , 2 P : 2 , 3 , 4 , 5 , 4 , 4	N : * P : 5 , 3 , 5 , 5 , 4 , 5
11.	*	*	*
12.	CNC , SL	CNC	CNC , Hand Made

Subject 16

Design-studio

1. Computers , Consumer Products ,

2. DM = 1 , ID = 2 , MD = 2 , GD = 1 , CP = 1

3. Major = ID , MD
Minor = G , CP

4. HDS = Conceptual , Idea test , Idea refine
2D = Engineering drawing
3D = Idea evaluation , Rend. ,
5. Engineering drawing

HDS
2D = Photoshop
6. 3D = Ideas

2D = FI , EC
3D = PF , F
Other = *
7.

2D = S , FS ,VM
3D = S , G , FS
Other = *
8.

9. 1 , 3

10. 1 , 2

N : 2 , 3 , 4 , 5 , 1
11. P : 3 , 4 , 5 , 5 , 3 , 5

*
12.

CNC

Subject 17

Design-house

1. Computers , Optical , Lighting , Communications ,

2. DM = 1 , ID = 4 , MD = 4

3. Major = ID , MD , MM
Minor = T & E

4. HDS = Conceptual , Idea refine
2D = Idea test , Engineering drawing
3D = Conceptual , Idea refine ,
5. Rendering , Engineering drawing

HDS
6. 2D = Auto-CAD
3D = Solidwork

2D = FI , E
7. 3D = FI , PF , EC , F
Other = *

2D = S , Drafting
8. 3D = S , FS
Other = *

9. 1 , 3

10 1 , 2

11 N : 2 , 1 , 4 , 4 , 1
P : 3 , 4 , 5 , 5 , 5 , 5

12 *

CNC

Subject 18

Design-house

1. Consumer Products , Lighting , Medical equipment

2. DM = 1 , ID =5
GD = 2

3. Major = G , ID
Minor = CP , MD

4. HDS = Conceptual , Rendering
2D = Rendering,Eng. Drw.,
3D = Conceptual , Idea refine ,
Idea evaluation ,
5. Render , Engineering drawing

HDS
6. 2D = Coreldraw , Photoshop
3D = Alias , 3D Studio

2D = FI , E
3D = FI , PF , EC , F
Other = *
7.

2D = S , Letter Form , G
8. 3D = S , FS , VM
Other = *

9. 1 , 2

10 2 , 3

11 N : 1 , 1 , 4 , 4 , 1
P : 3 , 3 , 5 , 4 , 3 , 5

12 *

CNC

	Subject 19 Design-studio	Subject 20 Design-studio	Subject 21 Design-studio
1.	Computers , Consumer Products , Lighting , Hand tools & equipment Toys	Computers , Communications, Clocks & Watches , Lighting , Toys	Computers , Communications, Medical equipment . Optical
2.	ID = 2	DM = 1 , ID = 2 , MD = 1	DM = 1 , ID = 2 , GD = 1
3.	Major = ID Minor = G , CP	Major = ID , MD Minor = DR	Major = G ,ID Minor = CP
4.	HDS = Conceptual , Rendering 2D = Conceptual , Idea refine 3D = Idea test , Idea evaluation , Rendering	HDS = Conceptual , Rendering 2D = Conceptual , Rendering , Engineering drawing 3D = Conceptual , Idea test , Idea refine , Idea evaluation , Rendering , Engineering drawing	HDS = Conceptual , Rendering 2D =Engineering drawing 3D = Idea test , Idea refine , Idea evaluation , Rendering , Engineering drawing
5.	HDS 2D = Auto-CAD , Coreldraw , Photoshop 3D = Alias	HDS 2D = Auto-CAD 3D = Alias , PRO-E	HDS 2D = * 3D = *
6.	2D = E 3D = FI , PF , EC , F Other = *	2D = E 3D = FI , PF , EC Other = *	2D = E , FI 3D = FI , PF , EC Other = *
7.	2D = S , Drafting 3D = S , VM Other = *	2D = S 3D = S , FS , MD Other = *	2D = S , Drafting , G 3D = S , FS , VM , Drafting Other = *
8.	1 , 2	1 , 3	1
9.	1 , 2	1	2
10.	N : 1 , 1 , 3 , 4 , 1 P : 2 , 3 , 5 , 4 , 5 , 5	N : 1 , 1 , 4 , 4 , 2 P : 2 , 3 , 5 , 3 , 4 , 5	N : 1 , 1 , 5 , 4 , 1 P : 2 , 3 , 5 , 5 , 5 , 5
11.	*	*	*
12.	CNC , Hand Made	CNC	CNC , Hand Made

Appendix C: The design objectives of a driving assistance device

(1) Marketing
  a. Reaching the market share of 15% within one year
  b. The cost of each piece should not be over $1.5.
  c. The selling price is about $5 to $7
  d. It should be equipped with a new or improved function better than the current products in the market.

(2) Users and their needs
  a. The target users will be the drivers with the age range of 20 to 45.
  b. It should be easy to install in the steering wheel and reach the stability requirement.
  c. The product form should meet the comfort requirement and reduce the tiredness of holding for a long period of time.
  d. When it is installed, it should not interfere with the diver's operation of the steering wheel. Neither noise nor looseness should occur.

(3) Safety
  a. No sharp edge or protruding part in the product form.
  b. It should be designed to operate only when it is securely installed.
  c. The material should be able to bear an impact of 200kg/m^2.
  d. No harmful material should be used in the finish.

(4) Form
  a. The form should be unique and offer a sense of pleasure.
  b. The form should add value to the product.
  c. It should be of a holistic shape.
  d. The form should be neutral, not too fashionable.
  e. The form should not be too biologic (e.g., like an animal or a tree).
  f. The form should properly match the interior of the car.

(5) Colour and texture
  a. Dual tone is recommended.
  b. Both vivid and solemn colours should be considered.
  c. The Pantone colour system should be adopted.
  d. The texture should be user friendly and comfortable.
  e. The texture should not be too rough or rugged.
  f. Cost and production technology for colour and texture should be considered.

(6) Material
  a. Durable ABS plastic should be used in the holding part.
  b. The chassis fastened to the driving wheel should be reinforced fiberglass or aluminum (can bear the impact of 200 kg/m^2).

(7) Production technology and requirements
  a. Plastic parts should be made by injection.
  b. Injection (FRP) or pressure casting (aluminum) should make the chassis.
  c. The components inside should be made by metal pressing technique so as to cost down.
  d. No more then 10 steps should be required in assembly. No more than 3 screws are required to fasten the product.

(8) Shipping requirement
  a. The product size should not be too big. A full-size container should be able to load 1000-1200 pieces.

Appendix D: The design objectives of Back Cushioning Massager

1. The users in the American market with the year range of 30 up to the aging group are the target population.

2. Market price: $60.00.

3. The product should meet the security requirements of the UL regulation.

4. It uses six shaking motors on the shoulders, back sides, and waist sides.

5. The product is operated by a hand controller.

6. The product form and size should meet the requirements of regular chairs and car seats.

7. A style of warmth and comfort should be offered for the product form.

8. The color should be moderate and simple so as to fit the car interior and home decoration.

9. In each massager, there are six independent shaking boxes stringed together. These shaking motors is wrapped with cotton and then covered with the fireproof plastic fiber.

10. The shell of the hand controller is made by injection molding at the cost under $1.50 a piece.

11. It should be easy to fasten or take down the Back Cushioning Massager from the chair without looseness or displacement.

12. To fit the location of car seat of American vehicles and user's habit, the electrical cord of hand controller should be placed on the right side of the Back Cushioning Massager.

13. No noise except that of shaking should be made when used.

14. The strength of the hand controller shell should pass the dropping test where the piece, under the condition without packaging, should not break or fall to pieces when dropping from a altitude of 3 meters.

15. The surface of the Back Cushioning Massager should not have edges too sharp or too small lest the fiber should break when pressured or heated

Appendix E: The design objectives of Talking Clock

1. The target population of this product is set to be the middle-aged European businessmen who are frequently on travel.

2. Market price: ￡20.00.

3. It should meet the security regulation of UK, Germany, French, Austria, Swiss, and Italy.

4. The clock consists of a 2”X3” LCD display.

5. There should be a protection design for the LCD display.

6. The clock can be placed horizontally and vertically.

7. It uses 2 AAA type batteries.

8. Product dimensions: 7.0(W) X 10(L) X 1.50(H) cm.

9. The product form should be of simple, elegant, and a little bit fashionable style.

10. The clock uses ABS material and manufactured by injection molding.

11. The structure should be simple and strong.

12. The shell and LCD protection design should bear the pressure of 80 lb/m^2. There is no cracking or damage under such pressure.

13. The major color can represent the steady, calm, and dignified image of businessmen.

14. It is easy to store and saves space.

Appendix F: The design objectives of Night Light

1. It is positioned in the low price market for general American families.

2. Market price: $3.00.

3. The product should meet the security requirements of the UL regulation.

4. The product size should not be bigger than that of a double electrical outlet on the wall.

5. In addition to two pieces of EL, an electrical socket is offered.

6. It should be easy to plug in and out of the electrical outlet on the wall.

7. The diameter of the EL piece is 60 mm.

8. It is better that the finish is designed with a medium rough texture.

9. The number of the shell component should not bigger than two.

10. The cost of this product should be less than $0.80.

Appendix G: The design objectives of Power Adapter

1. The product is positioned mainly for the American automobile accessories market.

2. It is an ODM product for the Radio Shack Company.

3. Market price: $12.00.

4. It is used in a car with 24 V input and output. 12 options of voltage are offered.

5. The electrical cord can be stored.

6. It is suitable for mobile phones, digital cameras, PDA, and other portable electronic products.

7. The product should meet the security regulation of American Automobile Security Society.

8. The product form should fit the car interior and related electronic product form.

9. Five options of the electrical outlet can be offered.

10. The cost of the product is less than $5.00.

11. The product shell uses ABS as material and manufactured by injection molding.

12. It should bear the temperature of 85℃ and will function properly and not be deformed in this situation.

Appendix H-1: The sample of the raw protocol of design episode A

No	Design Development	Model construction	Dialogue	Timing	Action
1			I will do the contour profile of the top view.	0.22	Draw a circle and adjust the scale
2			Draw e1 according tot he standard dimension.	1.28	Discuss it by the rendering
3			But I don't know how to set the precise dimension now.	1.31	
4			So, you don't need to care about the precise dimension now.	1.36	
5			Just the rough shape!	1.40	
6			Rough. Then this is probably not covered.	1.42	
7			So it reads 54 and 47.	1.46	Pick object
8			It should work!	1.53	Set command parameter, delete the circle
9			Wrong.	2.26	Draw a circle
10			Pick object. I will enlarge the view.	2.34	Adjust the scale
11			Something weird.	2.45	Del the circle
12			Now the circle means the dimension or you have already started building the body.	3.06	Discuss with others
13			Oh, I just try the rough shape. My teacher had taught us how to adjust the correct dimensions. But I am not familiar with it.	3.11	
14			Ok, go ahead.	3.19	
15				3.25	Change the mouse
16			Start working.	3.48	
17			Now copy this one.	3.50	Duplicate circle
18			What you are drawing are the two panels? Yes.	4.06	Move circle

Appendix H-2: (1)The sample of coding history of model construction for design episode A

Time	First			Second			Arbitration			Dialogue
	Pd	Mi	Ma	Pd	Mi	Ma	Pd	Mi	Ma	
0.22	Ls	Ps	Td	Ls	Ps	Td	Ls	Ps	Td	I will do the contour profile of the top view.
1.28	Ls	Cl	Td				Sd	Cl	Td	Draw e1 according tot he standard dimension.
1.36	Sd	Pp	Td	Sd	Ju	Td	Sd	Pp	Td	So, you don't need to care about the precise dimension now.
1.40				Sd	Ps	Td	Sd	Dd	Td	Just the rough shape!
1.42							Sd	Dd	Td	Rough. Then this is probably not covered.
1.46	Sd	Ps	Td	Sd	Ca	Td	Sd	Ca	Td	So it reads 54 and 47.
1.53							Sd	Dd	Td	It should work!
2.26	Sd	Dd	Td	Sd	Dd	Td	Sd	Dd	Op	Wrong.
2.34	Sh	Ps	Td				Sh	Dd	Td	Pick object. I will enlarge the view.
3.19				Sd	Dd	Td	Sd	Dd	Td	Ok, go ahead.
3.50	Ls	Ps	Td	Ls	Ps	Td	Ls	Ps	Td	Now copy this one.
4.12							Sd	Dd	Td	But they are just rough shape.
4.23	Ls	Ps	Td	Ls	Ps	Td	Ls	Ps	Td	I am going to build a flat one with a rough shape.
8.02	Ls	Ps	Td	Ls	Ps	Td	Ls	Ps	Op	Or I will use some other way.
10.20	Ls	Dd	Td	Ls	Dd	Td	Ls	Dd	Td	I will delete it and do it over.
10.24	Ls	Ps	Td	Ls	Ps	Td	Ls	Cl	Td	I will use solid to do it.
11.00				Ls	Dd	Td	Ls	Dd	Td	I need to have a column adjust its scale
11.20							Ls	Dd	Td	Copy it.
11.50	Ls	Ps	Td	Ls	Ps	Td	Ls	Ps	Td	Then build a rectangular cube.
12.02	Ls	Dd	Td	Ls	Ps	Td	Ls	Ps	Td	Enlarge it.
12.37	Ls	Ps	Td	Ls	Ps	Td	Ls	Cl	Op	I will use solid to build it and merge them together.
13.09				Ls	Dd	Td	Ls	Dd	Td	Merge.
14.20	Ls	Ka	Td	Ls	Ka	Td	Ls	Ka	Td	I need to look up the operation from the manual
14.59	Sd	Dd	Op	Sd	Ps	Op	Sd	Dd	Op	I delete all elements of model and rebuilt it

(2) The sample of coding history of design development for design episode A

Time	First			Second			Arbitration			Dialogue
	Pd	Mi	Ma	Pd	Mi	Ma	Pd	Mi	Ma	
0.22	S	Ps	De	S	Ps	De	S	Ps	De	I will do the contour profile of the top view.
1.28	Si	De	De	Si	Ps	De	Si	Ps	De	Draw e1 according tot he standard dimension.
1.31				Si	Ju	De	Si	Cl	De	But I don't know how to set the precise dimension now.
1.36				Si	La	De	Si	La	De	So, you don't need to care about the precise dimension now.
1.40				Si	Ps	Td	Si	Dd	Td	Just the rough shape!
1.46	Si	Ju	Td	Si	Ju	Td	Si	Ju	Td	So it reads 54 and 47.
1.53				Si	Ev	Td	Si	Dd	Td	It should work!
2.26	Si	Dd	Td	Si	Dd	Td	Si	Dd	Td	Wrong.
2.34	Si	Ps	Td	Si	Dd	Td	Si	Dd	Td	Pick object. I will enlarge the view.
3.19	Si	Dd	Td	Si	Dd	Td	S	Dd	Td	Ok, go ahead.
3.50	S	Ps	Td	S	Ps	Td	S	Ps	Td	Now copy this one.
4.12	S	Ps	Op				S	Ps	Op	But they are just rough shape.
8.02	S	Ps	Op	S	Dd	Op	S	Ps	Op	Or I will use some other way.
10.20	S	Dd	Td	S	Dd	Td	S	Dd	Td	I will delete it and do it over.
10.24	S	Ps	Td	S	Ps	Td	S	Ps	Td	I will use solid to do it.
12.37	S	Ps	Td	S	Ps	Op	S	Ps	Op	I will use solid to build it and merge them together.
13.09				S	Dd	Td	S	Dd	Td	Merge.
18.05	S	Ps	Td	S	Ps	Td	S	Ps	Td	I will delete the circle.
18.57							S	Kd	Td	In a new version of Alias, you can directly draw an object. Then decide whether thee is an opening shell shape. You don't need to explode the circle and delete it.
19.20	S	Kd	Td				S	Kd	Td	I couldn't find the command I need in the manual.
19.50	S	Ev	Td	S	Ev	Td	S	Ev	Td	But it's not quite right.
26.50	S	Dd	Td	S	Dd	Td	S	Dd	Td	I made it.
28.35	S	Ps	Td	S	Ps	Td	S	Ps	Td	Now I cut the circle into halves and duplicate it symmetrically.

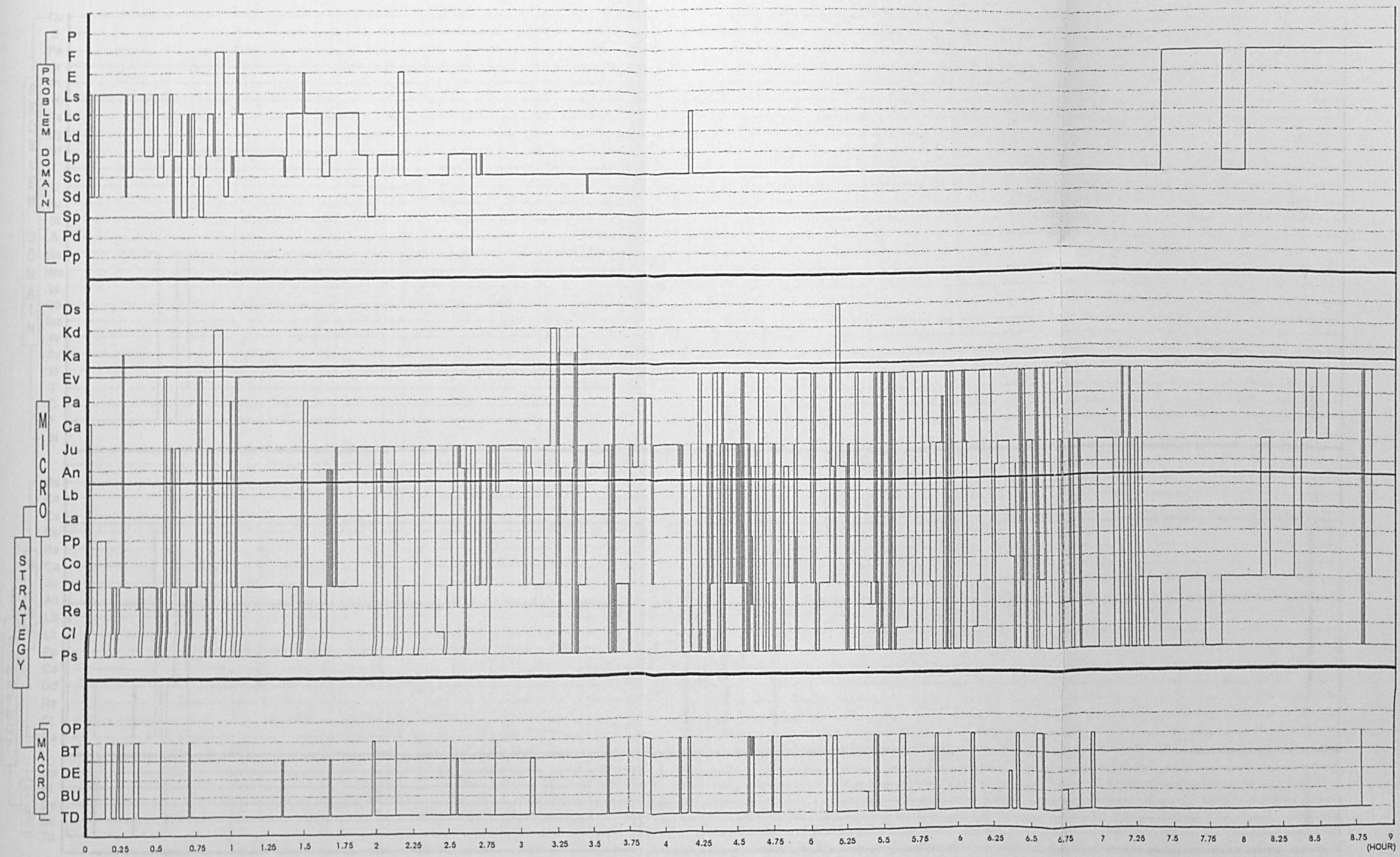
Appendix H-3: The final encoded protocol of model construction task for design episode A

Time	PD	MI	Ma	Dialogue	Actions
0.22	Sh	Ps	Td	I will do the contour profile of the top view.	Draw a circle and adjust the scale
1.28	Sd	Cl	Td	Draw e1 according tot he standard dimension.	Discuss it by the rendering
1.36	Sd	Pp	Td	So, you don't need to care about the precise dimension now.	
1.40	Sd	Dd	Td	Just the rough shape!	
1.42	Sd	Dd	Td	Rough. Then this is probably not covered.	
1.46	Sd	Ca	Td	So it reads 54 and 47.	Pick object
1.53	Sd	Dd	Td	It should work!	Set command parameter, delete the circle
2.26	Sd	Dd	Op	Wrong.	Draw a circle
2.34	Sh	Dd	Td	Pick object. I will enlarge the view.	Adjust the scale
3.19	Sd	Dd	Td	Ok, go ahead.	
3.50	Sh	Ps	Td	Now copy this one.	Duplicate circle
4.12	Sd	Dd	Td	But they are just rough shape.	
4.23	Sh	Pp	Td	I am going to build a flat one with a rough shape.	Create a surface and adjust scale
8.02	Sh	Ps	Op	Or I will use some other way.	
10.20	Sh	Dd	Td	I will delete it and do it over.	Del two circles and surface
10.24	Sh	Cl	Td	I will use solid to do it.	Set command parameter
11.00	Sh	Dd	Td	I need to have a	Create a cylinder and adjust scale

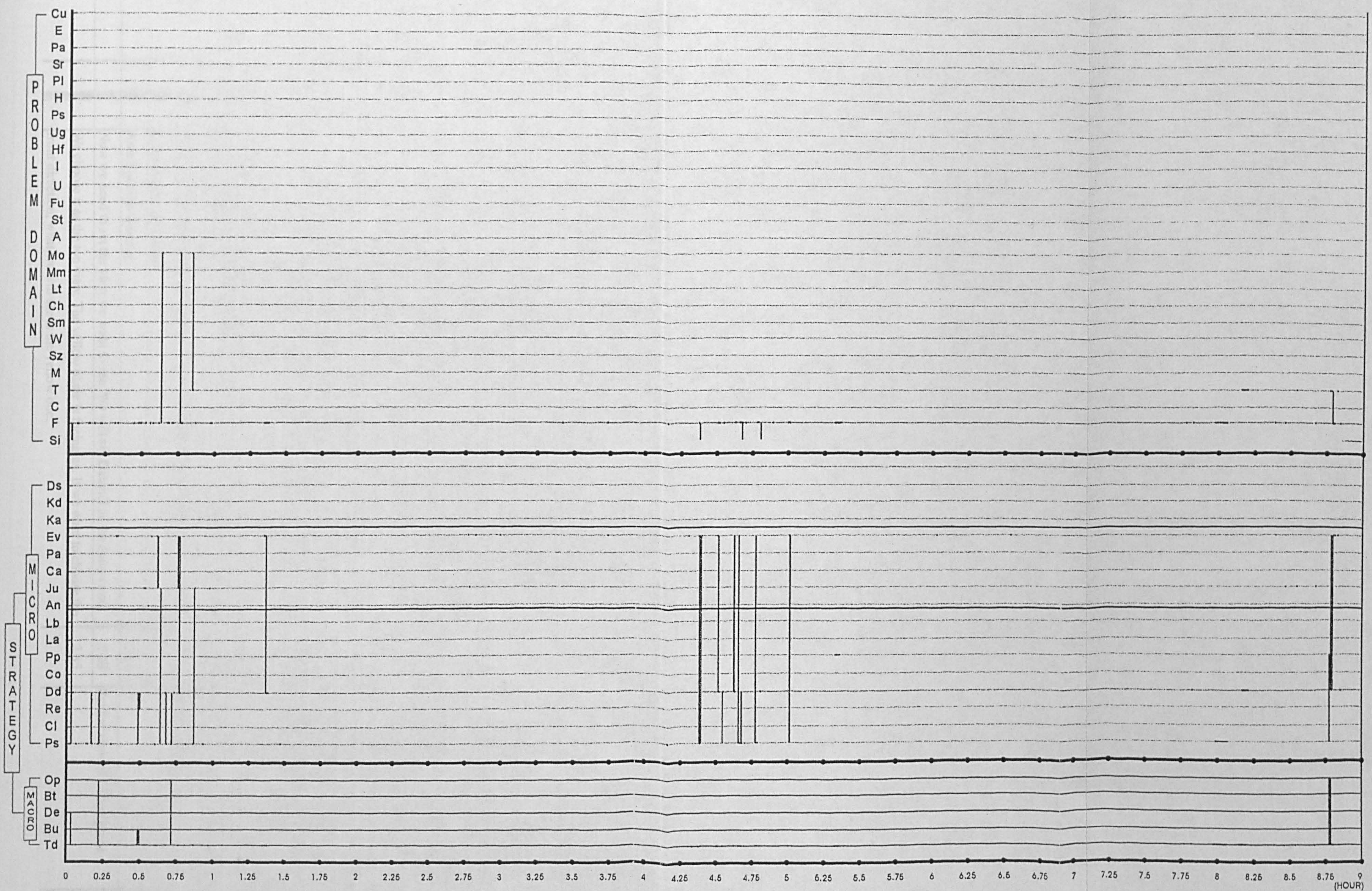
Appendix H-4: The final encoded protocol of design development for design episode A

Time	PD	MI	Ma	Dialogue	Actions
0.22	S	Ps	De	I will do the contour profile of the top view.	Draw a circle and adjust the scale
1.28	Si	Ps	De	Draw e1 according tot he standard dimension.	Discuss it by the rendering
1.31	Si	Cl	De	But I don't know how to set the precise dimension now.	
1.36	Si	La	De	So, you don't need to care about the precise dimension now.	
1.40	Si	Dd	Td	Just the rough shape!	
1.46	Si	Ju	Td	So it reads 54 and 47.	Pick object
1.53	Si	Dd	Td	It should work!	Set command parameter, delete the circle
2.26	Si	Dd	Td	Wrong.	Draw a circle
2.34	Si	Dd	Td	Pick object. I will enlarge the view.	Adjust the scale
3.19	S	Dd	Td	Ok, go ahead.	
3.50	S	Ps	Td	Now copy this one.	Duplicate circle
4.12	S	Ps	Op	But they are just rough shape.	
8.02	S	Ps	Op	Or I will use some other way.	
10.20	S	Dd	Td	I will delete it and do it over.	Del two circles and surface
10.24	S	Ps	Td	I will use solid to do it.	Set command parameter
12.37	S	Ps	Op	I will use solid to build it and merge them together.	Adjust scale
13.09	S	Dd	Td	Merge.	Find command

Appendix H-5： The activity chart of model construction task for design episode A



Appendix H-6 : The activity chart of design development for design episode A



Appendix I-1: The sample of the raw protocol of design episode B

No	Design Development	Model construction	Dialogue	Timing	Action
1			Nothing will be seen when you enter Pro-E.	0.25	Create a new file
2			Create a new file after entering Pro-E.	0.30	
3			What we are going to construct belongs to part.	0.37	
4			Give it a file name pri.part.	0.41	
5			We can also choose the file already built or choose to rebuild it. Here we choose rebuild.	0.54	
6			The window becomes empty after selection.	1.03	A function palette prompt
7			Now I am going to build 3 base planes x、y、z, three at a time.	1.12	Create the base plane
8			Then we choose feature. If we choose Define, the intersection of three base planes will be set as the initial point. We can also use offset to control the relative distance between planes and initial point.	1.17	
9			The plane with Datum is the so-called base plane.	1.27	
10			Now create three planes.	1.44	
11			Then open the igs files previously made in CorelDraw and transferred to Rhino and transferred to igs format.	1.50	Open a drawing file
12			Now I get the drawing.	2.14	
13			Now we need to set the view we want to see. We will set Datum3 as the front view.	2.20	Set the view of Datum plane
14			We choose it as the top view. The yellow plane is facing us. If we want to choose the front direction, what we will see is the yellow one.	2.35	

Appendix I –2: **(1)The sample of coding history of model construction for design episode B**

Time	First			Second			Arbitration			Dialogue
	Pd	Mi	Ma	Pd	Mi	Ma	Pd	Mi	Ma	
1.12	Ps	Ps	Td	Pp	Ps	De	Ps	Ps	De	Now I am going to build 3 base planes x、y、z, three at a time.
1.17	Ps	Ju	De	Ps	Ju	De	Ps	Ju	De	Then we choose feature. If we choose Define, the intersection of three base planes will be set as the initial point. We can also use offset to control the relative distance between planes and initial point.
1.44							Ps	Dd	De	Now create three planes
1.50	Lp	Ju	Td	Lp	An	Td	Lp	Ju	Td	Then open the igs files previously made in CorelDraw and transferred to Rhino and transferred to igs format.
2.20	Lp	An	Td	Lp	Ps	Td	Lp	Ps	Td	Now we need to set the view we want to see. We will set Datum3 as the front view.
3.23	Pp	Dd	Td	Pp	An	Td	Pp	Dd	Td	Checking from top or side view.
5.45	Lp	Ps	Td	Lp	Ps	Td	Lp	Ps	Td	First we will choose four lines.
5.54				F	Pd	Td	F	Dd	Td	Create a solid first.
6.03	Lp	Ps	Td	Lp	Ju	Td	Lp	Ps	Td	If there is no line, we have to draw ourselves. Now we are going to tracing drawing, to rebuild it.
7.12	Lp	An	Td	Lp	Ps	Td	Lp	Ps	Td	First make a vertical central line align to the surface.
7.43	Lp	Ju	Td	Lp	An	Td	Lp	Ju	Td	Sketch the shape without considering the dimensions. Draw the lines first
8.21	Lp	Ju	Td	Lp	An	Td	Lp	Ju	Td	Just checking without using its parameter. Then draw an arc close to it.
8.57	Lp	An	Td	Lp	An	Td	Lp	An	Td	It seems that every part is interrelated to others. So I will close and trim part of it.
9.13				Ld	Ps	Td	Ld	Ps	Td	Then give the dimensions.
10.34	Ld	An	Td				Ld	Ju	Td	There is one dimension needed. Make sure there are four dimensions.
10.54	Ld	An	Td	Ld	Ju	Td	Ld	Ju	Td	Now adjust the dimensions.
11.39	Lp	Ps	Td	Lp	Ju	Td	Lp	Ju	Td	Make sure that the middle is the highest point (in value).
12.04	Lp	Dd	Td	Lp	Ps	Td	Lp	Ps	Td	Skip the side curve. Use the line on the side to offset and trim it. Forget about the distance.

(2) The sample of coding history of design development for design episode B

Time	First			Second			Arbitration			Dialogue
	Pd	Mi	Ma	Pd	Mi	Ma	Pd	Mi	Ma	
6.56				S	Ps	Td	S	Ps	Td	Change the view port to the working surface. We are going to trace the shape.
7.43	Si	Ps	Td	Si	Dd	Td	Si	Dd	Td	Sketch the shape without considering the dimensions. Draw the lines first
8.21	Si	Ev	Td	Si	Ev	Td	Si	Ev	Td	Just checking without using its parameter. Then draw an arc close to it.
8.37							S	Ju	Td	Similarly, trace and mirror it to the left.
10.54	Si	Dd	Td	Si	Dd	Td	Si	Ps	Td	Now adjust the dimensions.
11.39	Si	Ju	Td	Si	Ju	Td	Si	Ju	Td	Make sure that the middle is the highest point (in value).
23.10	Si	An	Td	Si	Ev	Td	Si	Ev	Td	We can see that the distance between the green line and white line is different. This means that it was not precise when it was done in CorelDraw.
30.11	S	An	Td	S	Ju	Td	S	Ju	Td	There is some change in the back part.
31.59	F	Ps	Td	F	Ps	Td	F	Ps	Td	What we are doing is the single component. Then we need to combine these components.
37.23	S	Ps	Td	S	Dd	Td	S	Dd	Td	Start tracing.
1:11:20	Si	Ps	Td	Si	Ps	Td	Si	Ps	Td	Make sure the dimensions on the top first.
1:17:14	S	Ju	Td	S	Ev	Td	S	Ev	Td	The left and right parts are not symmetrical.
1:32:00	Si	Ev	Td	Si	Ev	Td	Si	Ev	Td	100 is too small. Make it 500. Copy another piece and merge them together.
1:41:50	Si	Ju	Td	Si	Ju	Td	Si	Ev	Td	It's skewed. Make it smaller. A little bit smaller. It's done now.
1:42:35	S	Ps	Td	S	Ps	Td	S	Ps	Td	How about the side section? We will skip it now.
1:49:08	S	Ev	Td	S	Ev	Td	S	Ev	Td	Is it a wave shape? No, just rounded edge. First set the draft angle and do fillet last.

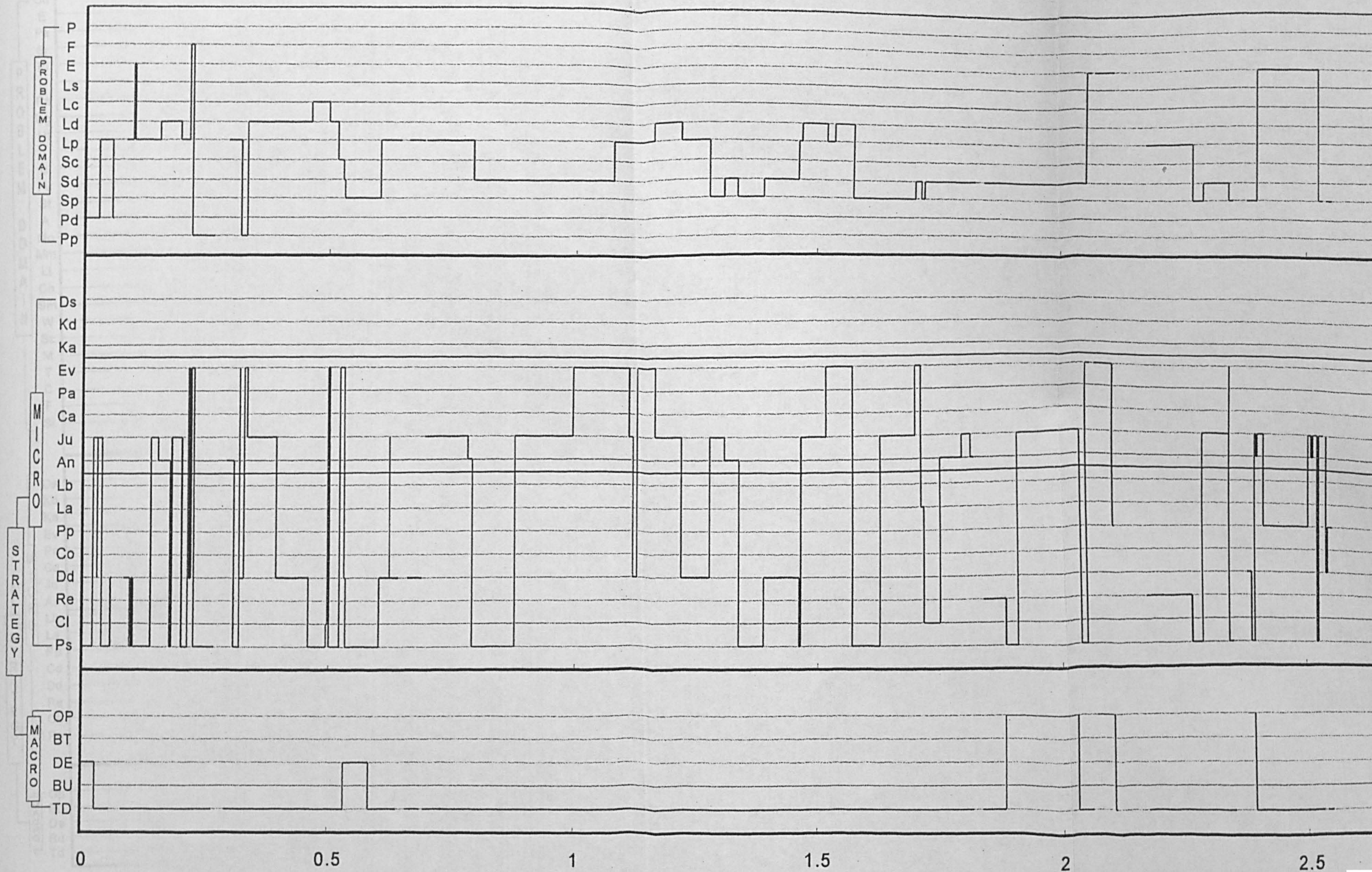
Appendix I -3: The final encoded protocol of model construction task for design episode B

Time	PD	MI	Ma	Dialogue	Actions
1.12	Ps	Ps	De	Now I am going to build 3 base planes x 、y 、z, three at a time.	Create the base plane
1.17	Ps	Ju	De	Then we choose feature. If we choose Define, the intersection of three base planes will be set as the initial point. We can also use offset to control the relative distance between planes and initial point.	
1.44	Ps	Dd	De	Now create three planes	
1.50	Lp	Ju	Td	Then open the igs files previously made in CorelDraw and transferred to Rhino and transferred to igs format.	Open a drawing file
2.20	Lp	Ps	Td	Now we need to set the view we want to see. We will set Datum3 as the front view.	Set the view of Datum plane
3.23	Ps	Dd	Td	Checking from top or side view.	Set the view of Datum plane
5.45	Lp	Ps	Td	First we will choose four lines.	Start tracing drawing
5.54	F	Dd	Td	Create a solid first.	Tracing drawing
6.03	Lp	Ps	Td	If there is no line, we have to draw ourselves. Now we are going to tracing drawing, to rebuild it.	
7.12	Lp	Ps	Td	First make a vertical central line align to the surface.	Tracing drawing
7.43	Lp	Ps	Td	Sketch the shape without considering the dimensions. Draw the lines first	Tracing drawing
8.21	Lp	Ju	Td	Just checking without using its parameter. Then draw an arc close to it.	
8.57	Lp	Ju	Td	It seems that every part is interrelated to others. So I will close and trim part of it.	Tracing drawing
9.13	Lp	An	Td	Then give the dimensions.	Dimensioning
10.34	Ld	Ps	Td	There is one dimension needed. Make sure there are four dimensions.	
10.46	Ld	Ju	Td	When everything is secure, we will set the thickness. Then it will regenerate.	Create a solid

Appendix I -4: The final encoded protocol of deign development for design episode B

Time	PD	MI	Ma	Dialogue	Actions
6.56	S	Ps	Td	Change the view port to the working surface. We are going to trace the shape.	Tracing drawing
7.43	Si	Dd	Td	Sketch the shape without considering the dimensions. Draw the lines first	Tracing drawing
8.21	Si	Ev	Td	Just checking without using its parameter. Then draw an arc close to it.	
8.37	S	Ju	Td	Similarly, trace and mirror it to the left.	Mirror
10.54	Si	Ps	Td	Now adjust the dimensions.	Adjust dimensions
11.39	Si	Ju	Td	Make sure that the middle is the highest point (in value).	
23.10	Si	Ev	Td	We can see that the distance between the green line and white line is different. This means that it was not precise when it was done in CorelDraw.	View checking
30.11	S	Ju	Td	There is some change in the back part.	Adjust the dimension
31.59	F	Ps	Td	What we are doing is the single component. Then we need to combine these components.	
37.23	S	Dd	Td	Start tracing.	Tracing drawing
1:11:20	Si	Ps	Td	Make sure the dimensions on the top first.	(fine tuning)
1:17:14	S	Ev	Td	The left and right parts are not symmetrical.	(erase)
1:32:00	Si	Ev	Td	100 is too small. Make it 500. Copy another piece and merge them together.	
1:41:50	Si	Ev	Td	It's skewed. Make it smaller. A little bit smaller. It's done now.	
1:42:35	S	Ps	Td	How about the side section? We will skip it now.	
1:49:08	S	Ev	Td	Is it a wave shape? No, just rounded edge. First set the draft angle and do fillet last.	
1:50:15	Mo	Ps	Td	Deal with the draft angle with the base plane. First select the tilting surface and then the base plane. Oh. They are wrong. Do it over. Make it bigger, 10.	

Appendix I-5 : The activity chart of model construction design episode B



Appendix J-1: The sample of the raw protocol of design episode C

No	Design Development	Model construction	Dialogue	Timing	Action
1			Because this is a simple product, I will build it directly in Ideas.	Preparation has been done before recording	
2			Get the components necessary for construction.	0.09	Insert the component file
3			This component is saved in file and can be accessed if necessary.	0.12	
4			In Ideas, it is one of the database for a product.	0.20	
5			It will save the file as a layer.	0.35	
6			The name of the layer is part.	0.40	Key in Name
7			Insert the parts that are common.	0.52	Adjust view port
8			Is it 2D or 3D?	0.54	Rotate view port
9			The blue part in the back is the pc board, isn't it? Yes, it's the pc board.	1.04	Adjust view port
10			This part was available in advance.	1.09	
11			We can adjust it right away.	1.12	
12			It's parametric. You can adjust the parameter.	1.14	
13			What's the parameter for?	1.22	Adjust view port
14			For adjustment of shape.	1.25	
15			Hide the object.	1.32	Close component, evaluate the base lines, thinking

Appendix J -2 : The sample of coding history of model construction for design episode C

Time	First			Second			Arbitration			Dialogue
	Pd	Mi	Ma	Pd	Mi	Ma	Pd	Mi	Ma	
1.14	Lp	Ps	Td	Lp	Ps	Td	Lp	Ps	Td	It's parametric. You can adjust the parameter.
1.25	Lp	Ju	Td	Lp	Ju	Td	Lp	Ju	Td	For adjustment of shape.
1.35	Lp	An	Td	Lp	Ev	Td	Lp	An	Td	At this stage, I'll evaluate whether this form will be used in the wireframe. It will be saved in another file in Pro-E. Because I will need it later, I'll change it into a reference curve.
2:28				Sp	Ps	Td	Sp	Ps	Td	Yes, I'll set the thickness.
2:30	Sp	An	Td	Sp	An	Td	Sp	An	Td	I am going to shader the front curvature. These surfaces and solids can be separated at any time. I'll select the surface first.
2:55	Sp	Ju	Td	Sp	Ju	Td	Sp	Ju	Td	Because the inner component has been set, it's easier to deal with. I just need to open the file.
3:03				Sp	Ka	Td	Sp	Ps	Td	The surface I am building is related to the LCD.
3:09	Lp	Ps	Td	Lp	Ps	Td	Lp	Ps	Td	I'm using the border to calculate the form, so I need to project the border.
4:07	Lp	Ju	Td	Lp	Ps	Td	Lp	Ps	Td	Pick one randomly and set it tangent to this one. When it turns to blue, the shape is defined.
4:14	Ld	Cl	Td	Ld	Cl	Td	Ld	Cl	Td	Then I will adjust the dimension of the border.
5:07				Lp	Ps	Td	Lp	Ps	Td	Then I will use the curvature to cut it.
5:31	Lp	An	Td	Lp	Ps	Td	Lp	Ju	Td	After cutting, it's easier to do offset. And we can delete the other one.
6:54	Sp	Ps	Td	Sp	Ps	Td	Sp	Ps	Td	And I will shader the front surface.
7:20				Lp	La	Td	Lp	La	Td	I will use this line later.
8:20	Ls	Ju	Td				Ls	Ps	Td	This shape and the line on the side are sections.

(2) The sample of coding history of design development for design episode C

Time	First			Second			Arbitration			Dialogue
	Pd	Mi	Ma	Pd	Mi	Ma	Pd	Mi	Ma	
0.09	Pa	Ps	Td	Pa	Dd	Td	Pa	Ps	Td	Get the components necessary for construction.
1.25	Si	Ps	Td	Si	Ps	Td	Si	Ps	Td	For adjustment of shape.
2:55				Pa	Ju	Td	Pa	Ps	Td	Because the inner component has been set, it's easier to deal with. I just need to open the file.
4:22	Pa	Ju	Td	Pa	An	Td	Pa	Ju	Td	I did this so as to insert the screen.
5:49	Ls	Ju	Td	Ls	Ps	Td	Ls	Ps	Td	After that, I'll adjust the shape.
9:55	Ls	Ps	Td	Ls	Ps	Td	Ls	Ps	Td	I will adjust the shape at this moment.
9:59				Ls	Ju	Td	Ls	Ju	Td	Common products are made by two pieces. This piece is symmetrical to the other one.
13:38	Si	Ps	Td	Si	Ps	Td	Si	Ps	Td	Adjust the size.
15:47	Si	Ps	Td	Si	Ps	Td	Si	Ps	Td	I am setting the depth for the cover.
24.46	F	Ev	Td	F	Ev	Td	F	Ev	Td	The purpose is to check if the surface is smooth. Check it.
24.57	F	Ev	Td	F	Ev	Td	F	Ev	Td	It' s not smooth here.
25.26	F	Ju	Td	F	Ju	Td	F	Ju	Td	One more thing. The curve may be not big enough.
29.04	F	Ps	Td	F	Ps	Td	F	Ps	Td	I am going to set the part where the rounded edge changes.
38.19				Ls	Ev	Td	Ls	Ju	Td	They can be done together because the two sides are symmetrical.
41.58	Si	Dd	Td	Si	Ps	Td	Si	Ps	Td	Adjust the dimensions of the lower part.
42.13	Ls	Ev	Td	Ls	Ev	Td	Ls	Ps	Td	The upper and lower cases are entirely symmetrical.
43.21				Ls	Ps	Td	Ls	Ps	Td	I will try to drag the curvature for the side.
52.05	Si	Ju	Td	Si	Ju	Td	Si	Ju	Td	In this shape, the ring and the side are not attached to each other. They are independent. So there should be a 1mm clearance.

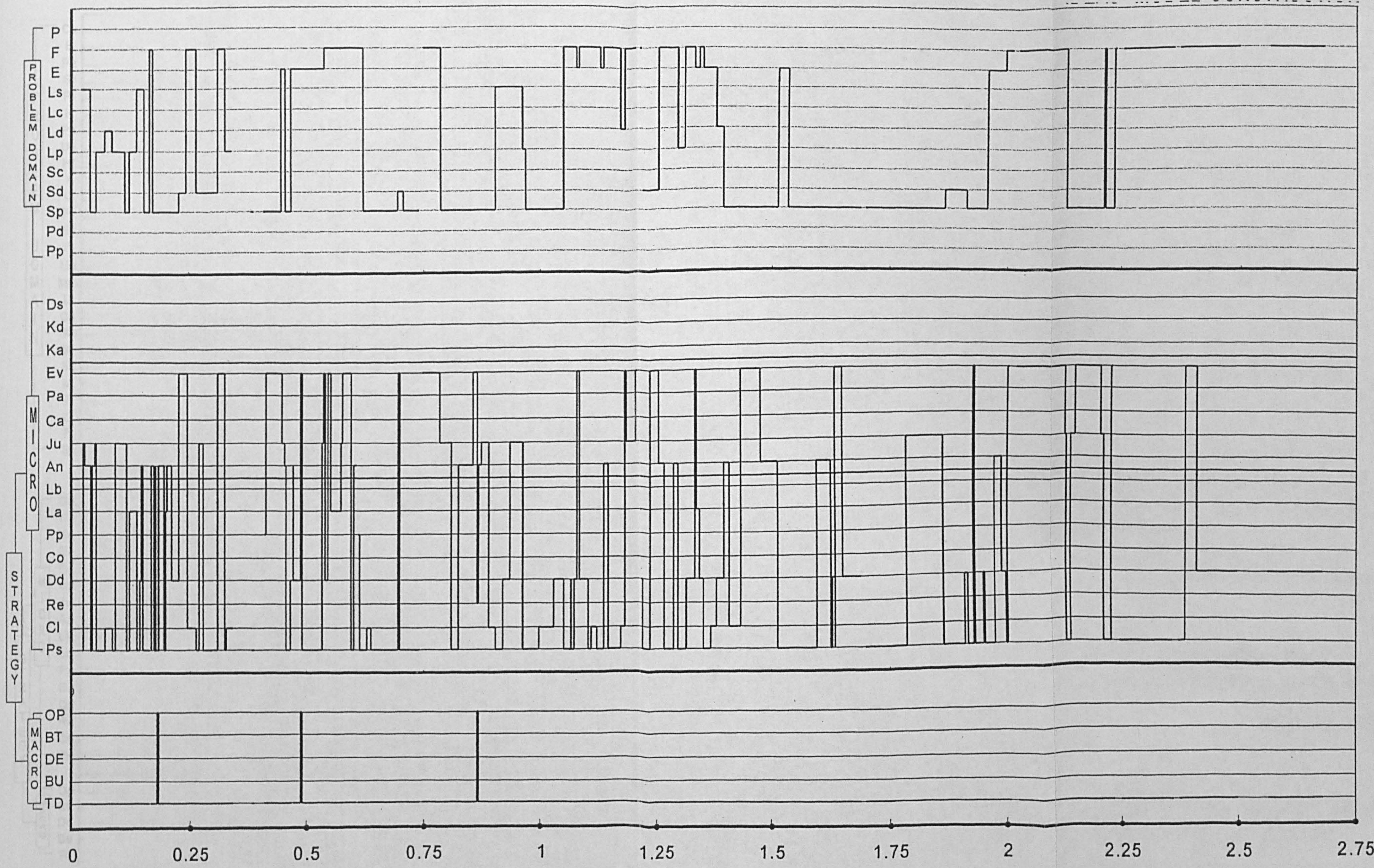
Appendix J-3: The final encoded protocol of model construction for design episode C

Time	PD	MI	Ma	Dialogue	Actions
1.12	Ps	Ps	De	Now I am going to build 3 base planes x 、y 、z, three at a time.	Create the base plane
1.17	Ps	Ju	De	Then we choose feature. If we choose Define, the intersection of three base planes will be set as the initial point. We can also use offset to control the relative distance between planes and initial point.	
1.44	Ps	Dd	De	Now create three planes	
1.50	Lp	Ju	Td	Then open the igs files previously made in CorelDraw and transferred to Rhino and transferred to igs format.	Open a drawing file
2.20	Lp	Ps	Td	Now we need to set the view we want to see. We will set Datum3 as the front view.	Set the view of Datum plane
3.23	Ps	Dd	Td	Checking from top or side view.	Set the view of Datum plane
5.45	Lp	Ps	Td	First we will choose four lines.	Start tracing drawing
5.54	F	Dd	Td	Create a solid first.	Tracing drawing
6.03	Lp	Ps	Td	If there is no line, we have to draw ourselves. Now we are going to tracing drawing, to rebuild it.	
7.12	Lp	Ps	Td	First make a vertical central line align to the surface.	Tracing drawing
7.43	Lp	Ps	Td	Sketch the shape without considering the dimensions. Draw the lines first	Tracing drawing
8.21	Lp	Ju	Td	Just checking without using its parameter. Then draw an arc close to it.	
8.57	Lp	Ju	Td	It seems that every part is interrelated to others. So I will close and trim part of it.	Tracing drawing
9.13	Lp	An	Td	Then give the dimensions.	Dimensioning
10.34	Ld	Ps	Td	There is one dimension needed. Make sure there are four dimensions.	
10.46	Ld	Ju	Td	When everything is secure, we will set the thickness. Then it will regenerate.	Create a solid

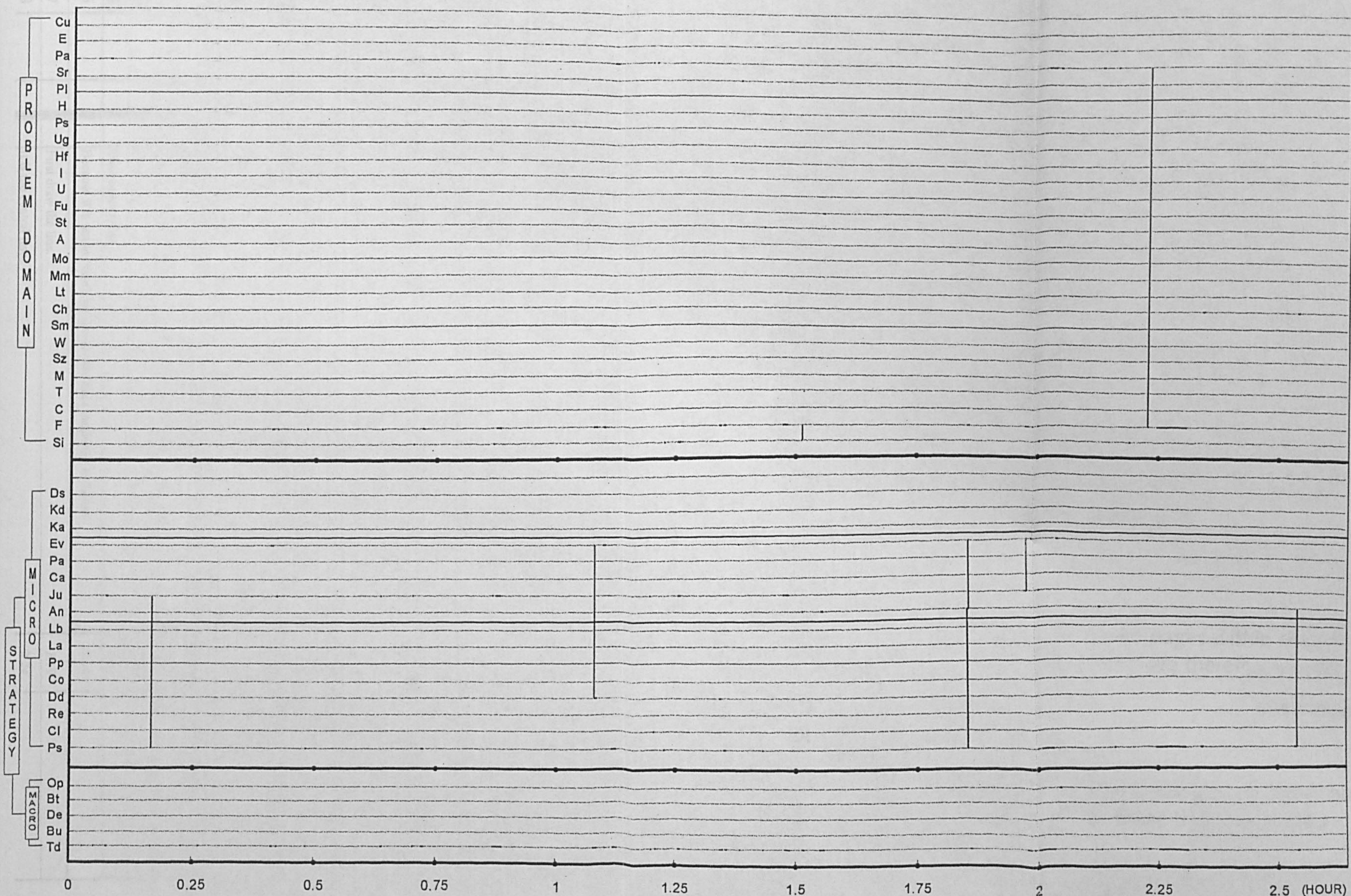
Appendix J-4: The final encoded protocol of design development task for design episode C

Time	PD	MI	Ma	Dialogue	Actions
0.09	Pa	Ps	Td	Get the components necessary for construction.	Insert the component file
1.25	Si	Ps	Td	For adjustment of shape.	Adjust view port
2:55	Pa	Ps	Td	Because the inner component has been set, it's easier to deal with. I just need to open the file.	Insert the LCD
4:22	Pa	Ju	Td	I did this so as to insert the screen.	Adjust dimensions
5:49	Ls	Ps		After that, I'll adjust the shape.	Build the bottom surface
9:55	Ls	Ps	Td	I will adjust the shape at this moment.	
9:59	Ls	Ju	Td	Common products are made by two pieces. This piece is symmetrical to the other one.	Picture still
13:38	Si	Ps	Td	Adjust the size.	Adjust the scale of the concave surface
15:47	Si	Ps	Td	I am setting the depth for the cover.	Select border→check direction→pick object→drag the curve→adjust→Key in dimensions (get ready for shadering)
24.46	F	Ev	Td	The purpose is to check if the surface is smooth. Check it.	Review
24.57	F	Ev	Td	It' s not smooth here.	
25.26	F	Ju	Td	One more thing. The curve may be not big enough.	Review
29.04	F	Ps	Td	I am going to set the part where the rounded edge changes.	Set radius for fillet
38.19	Ls	Ju	Td	They can be done together because the two sides are symmetrical.	Adjust the shape

Appendix J-5：The activity chart of model construction task design episode C



Appendix J-6： The activity chart of design development task for design episode C



Appendix K-1: The sample of the raw protocol of design episode D

No	Design Development	Model construction	Dialogue	Timing	Action
1			When the drawing is transferred into Rhino with DXF format, it is made up of uncontinuous lines.	0.11	
2			We, therefore, need to change it into what we want.	0.16	
3			First, we change the layer.	0.21	
4			Ctrl+A, and assign them to a new layer.	0.25	
5			Change it to a lighter color.	0.34	
6			Change it to a new layer.	0.46	
7			Make it light blue.	0.57	
8			Start tracing.	1.00	
9			Draw a circle first.	1.04	
10			Select 3 points randomly and draw a circle.	1.18	
11			Choose all objects.	1.25	
12			Move these objects.	1.32	
13			Click the initial point O.	1.40	
14			Then draw … …	1.59	
15			Two semi-circles.	2.02	
16			Because it is not in Pro-E, we can set the lines randomly in Rhino.	2.04	
17			First draw the line.	2.19	
18			It is the central line.	2.24	

Appendix K -2：(1) The sample of coding history of model construction for design episode D

Time	First			Second			Arbitration			Dialogue
	Pd	Mi	Ma	Pd	Mi	Ma	Pd	Mi	Ma	
0.16	Lp	Dd	Td	Lp	Ps	Td	Lp	Ps	De	We, therefore, need to change it into what we want.
0.21	Lp	Dd	Td	Ld	Ps	Td	Lp	Ps	De	First, we change the layer.
0.25				Lp	Ps	Td	Lp	Ps	De	Ctrl+A, and assign them to a new layer.
0.34	Lp	Dd	Td	Lp	Ps	Td	Lp	Ps	De	Change it to a lighter color.
0.46	Lp	Ps	Td	Lp	Ps	Td	Lp	Ps	De	Change it to a new layer.
0.57	Lp	Dd	Td	Lp	Ps	Td	Lp	Ps	De	Make it light blue.
1.00	Lp	Dd	Td	Lp	Dd	Td	Lp	Dd	Td	Start tracing.
2.04	Lp	Ju	Td	Lp	Ju	Td	Lp	Ju	Td	Because it is not in Pro-E, we can set the lines randomly in Rhino.
3.17	Lp	Dd	Td	Lp	Ps	Td	Lp	Ps	Td	Close this layer.
3.57	LP	Ps	Td	Lp	Dd	Td	Lp	Dd	Td	Then build the surface.
4.32				Lp	Ju	Td	Lp	Ju	Td	It's easy and precise to trace objects in Rhino.
5.04				Lp	Ps	Td	Lp	Ps	Td	It will be smooth when merged.
5.10	Lp	An	Td	Lp	An	Td	Lp	Ev	Td	It's tangent when the outer lines joined smoothly. It is, however, still on tracing process.
5.20	Lp	Dd	Td	Lp	La	Td	Lp	La	Td	The decorating scale detail will be dealt later. Now we will define the body.
6.13	Lp	Ps	Td							Select all lines.
6.50	Lp	An	Td	Lp	An	Td	Lp	Ev	Td	This part is not joined.
6.58	Lp	Ev	Td	Lp	Ev	Td	Lp	Ev	Td	There is some clearance.
7.15	Lp	Ps	Td	Lp	Ps	Td	Lp	Ps	Td	Use joint to fix it.
7.20	Lp	Ps	Td							Rebuild it by changing the parameter to 4.
7.38	Lp	An	Td	Lp	An	Td	Lp	Ev	Td	It should be smooth.
7.42	Ld	Ps	Td				Ld	Ps	Td	Zoom in and check.
7.48	Lp	Ju	Td	Lp	Ju	Td	Lp	Ju	Td	All lines are smooth, no like they were before.
8.18	Lp	Ps	Td	Lp	Ps	Td	Lp	Ps	Td	Now trace a line on the top.
8.40	Lp	Ps	Td	Lp	Lb	Td	Lp	Lb	Td	How will you build this part?

(2) The sample of coding history of design development for design episode D

Time	First			Second			Arbitration			Dialogue
	Pd	Mi	Ma	Pd	Mi	Ma	Pd	Mi	Ma	
4.32	F	Dd	Td	F	An	Td	F	Dd	Td	It's easy and precise to trace objects in Rhino.
5.20	Si	La	Td	Si	La	Td	Si	La	Td	The decorating scale detail will be dealt later. Now we will define the body.
8.46	Ls	Ps	Td	Ls	Ps	Td	Ls	Ps	Td	The shape here.
14.04	Ls	Ev	Td	Ls	Ka	Td	Ls	Ev	Td	Open the original drawing again.
14.16	Ls	Ps	Td	Ls	Ps	Td	Ls	Ps	Td	Let go for the side view. Because it's symmetrical, we can do only half part of it.
15.48	Ls	An	Td	Ls	Ev	Td	Ls	Ev	Td	It's not quite right.
15.50	Ls	Ev	Td	Ls	Ev	Td	Ls	Ev	Td	It won't by symmetrical then.
17.22	Ls	Cl	Td	Ls	Ev	Td	Ls	Cl	Td	It's changing all the time.
17.24	Ls	Ev	Td	Ls	Cl	Td	Ls	Ev	Td	It's naturally formed.
18.25	Pl	Ps	Td	Pl	Ps	Td	Pl	Ps	Td	What's we are doing now is the parting line.
20.12	Si	An	Td	Si	Ju	Td	Si	Ju	Td	It will be smaller.
20.20	F	Ev	Td	F	Ev	Td	F	Ev	Td	I think it will look better if it is compact.
21.12	Pl	Ev	Td	Pl	Ev	Td	Pl	Ev	Td	I mean the molding angle.
21.16	Pa	Cl	Td	Pa	Cl	Td	Pa	Cl	Td	There should be 4 parts.
21.23	Pl	Ev	Td				Pl	Ev	Td	But this side should match the surface and there will be no problems for molding angle.
21.32							Pl	Ev	Td	It will be about this long.
21.41	Pl	Dd	Td	Pl	Dd	Td	Pl	Dd	Td	Now this line is our parting line.
21.47	Ls	An	Td				Ls	An	Td	In the original drawing, this arc is on the top of a point.
21.56				H	An	Td	H	An	Td	So we don't have this section.
22.00				H	Ev	Td	H	An	Td	Actually, its vertex is on this side.
22.05	H	An	Td	H	An	Td	H	An	Td	We should be able to see it.
22.22	Pl	Ev	Td	Pl	An	Td	Pl	An	Td	Then you have to figure out first what the surface of the parting line is like.
22.25	Pl	An	Td	Pl	An	Td	Pl	An	Td	There will be no problem if we can set it in the beginning of drawing.

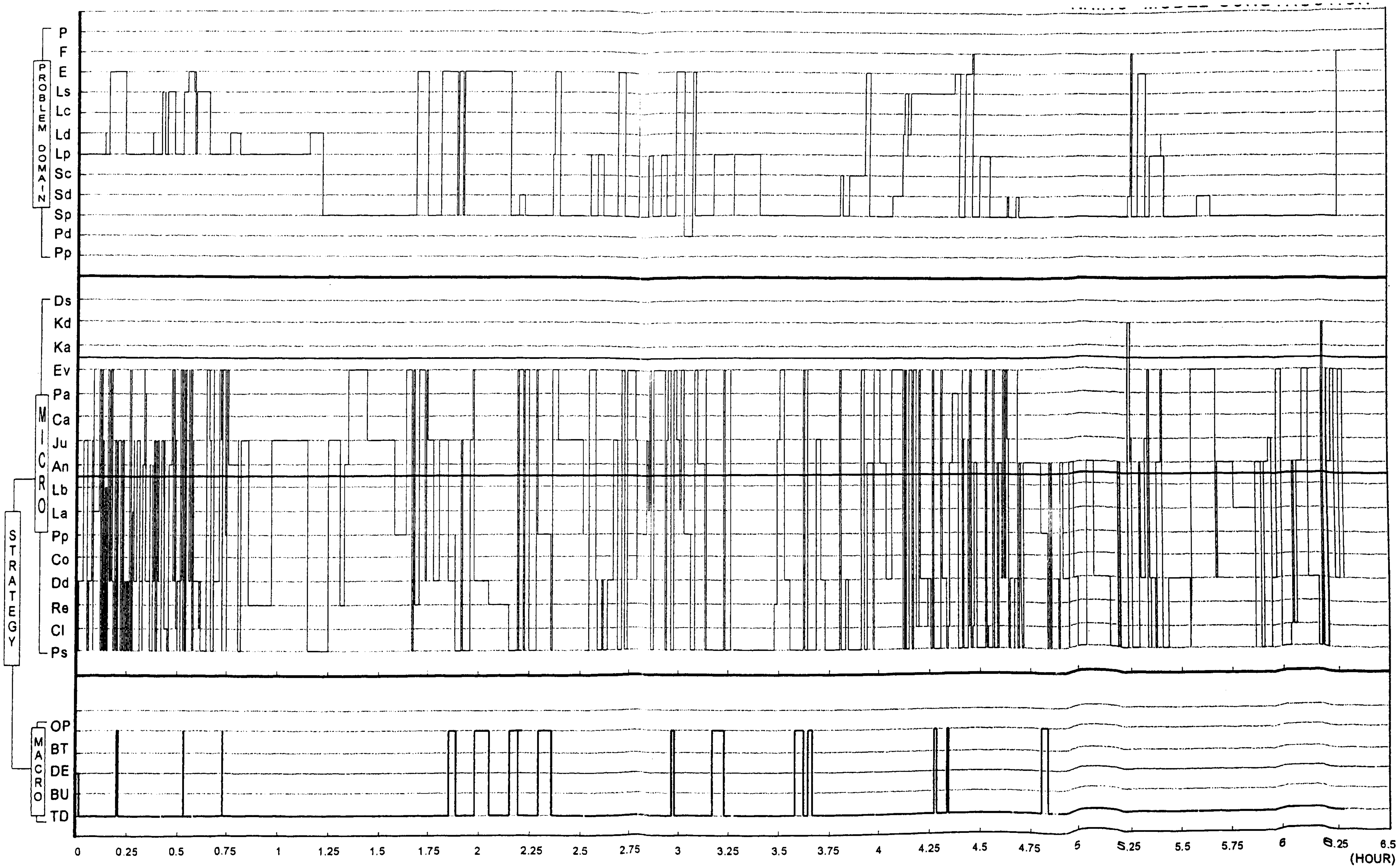
Appendix K-3: The final encoded protocol of model construction task or design episode D

Time	PD	MI	Ma	Dialogue	Actions
26.42	Ls	Cl	Td	Now we don't have a form for it.	Build reference lines (use a 45-degree line to generate the bottom view) for the first section
26.58	Ls	Ps	Td	We need to calculate it by engineering drawing.	
27.43	Ls	An	Td	Now I am trying to guess what it looks like.	
28.26	Lp	Ju	Td	Check the angle in this part.	Build reference lines (use a 45-degree line to generate the bottom view) for the first section
28.34	Lp	Ev	Td	And it is 1.5 degrees on this side.	
28.42	Lp	Dd	Td	It is close to 1.5. Actually it measures a little more than 1.4.	
28.48	Lp	Ev	Td	It's 2 from this side. What about the other side?	
28.52	Lp	Ev	Td	1.4.	
28.55	Lp	Ev	Td	Isn't it 88.6 degrees?	
28.58	Lp	Ev	Td	Yes, but it's on the other side.	
29.11	Lp	Dd	Td	10 degrees.	
29.14	Lp	Dd	Td	So this will be a little small than 1.5 degrees.	
29.27	Lp	Ju	Td	It can't extend to this far. Otherwise, it will be a problem.	Build reference lines to get the slopes of the sides in bottom view
29.51	Lp	Cl	Td	Isn't it strange?	
30.05	Lp	Ps	Td	It will be better if we change the angle to 1.5.	
30.07	Lp	Dd	Td	A little smaller.	
30.47	Lp	Dd	Td	Set it 0.5.	Build reference lines to get the slopes of the sides in bottom view
30.56	Lp	Ju	Td	But there is a round edge.	

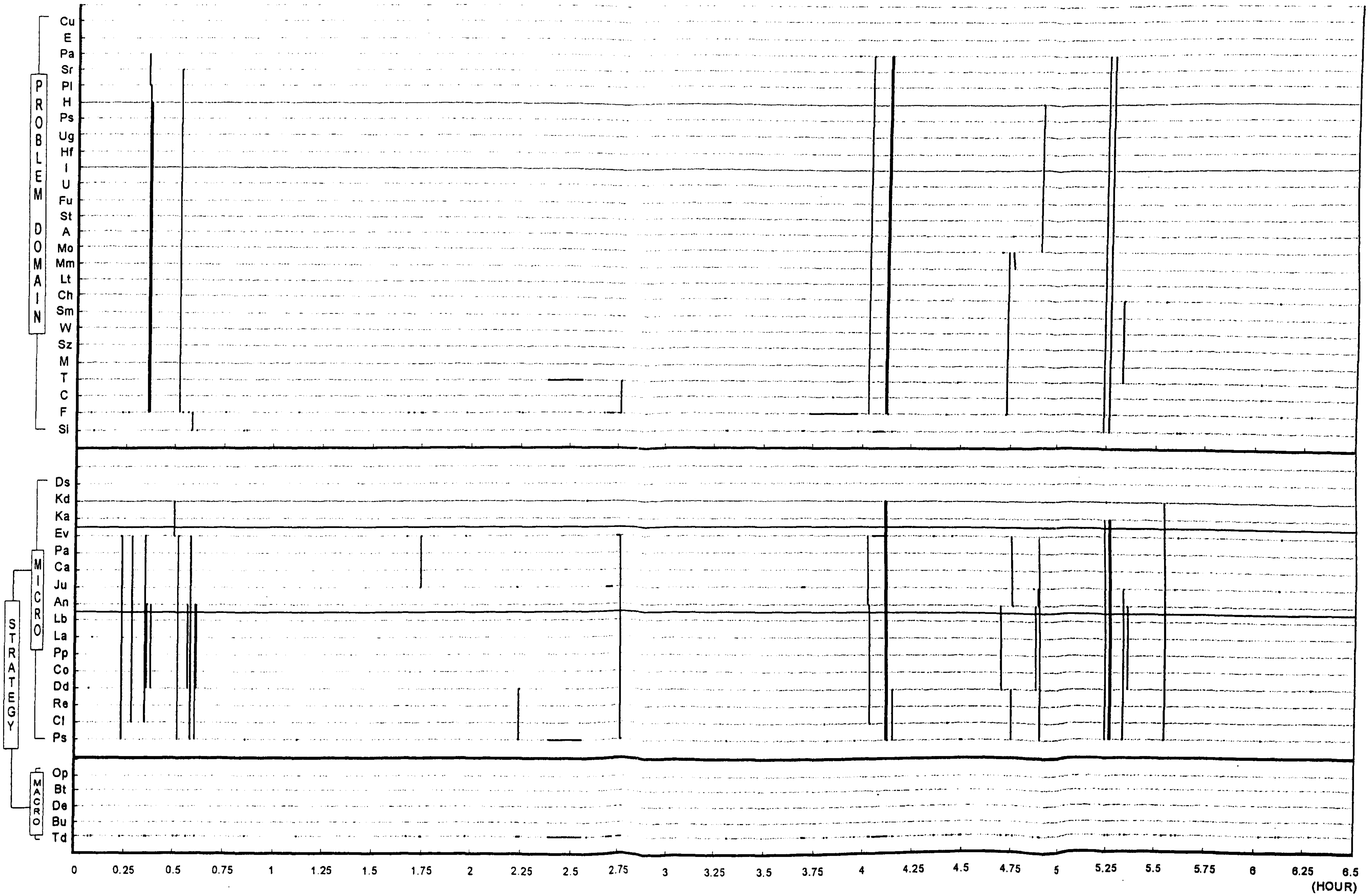
Appendix K-4: The final encoded protocol of design development task for design episode D

Time	PD	MI	Ma	Dialogue	Actions
4.32	F	Dd	Td	It's easy and precise to trace objects in Rhino.	
5.20	Si	La	Td	The decorating scale detail will be dealt later. Now we will define the body.	
8.46	Ls	Ps	Td	The shape here.	
14.04	Ls	Ev	Td	Open the original drawing again.	Explain command
14.16	Ls	Ps	Td	Let go for the side view. Because it's symmetrical, we can do only half part of it.	
15.48	Ls	Ev	Td	It's not quite right.	
15.50	Ls	Ev	Td	It won't by symmetrical then.	
17.22	Ls	Cl	Td	It's changing all the time.	
17.24	Ls	Ev	Td	It's naturally formed.	
18.25	Pl	Ps	Td	What's we are doing now is the parting line.	
20.12	Si	Ju	Td	It will be smaller.	
20.20	F	Ev	Td	I think it will look better if it is compact.	
21.12	Pl	Ev	Td	I mean the molding angle.	
21.16	Pa	Cl	Td	There should be 4 parts.	
21.23	Pl	Ev	Td	But this side should match the surface and there will be no problems for molding angle.	Use finger to draw on the screen
21.32	Pl	Ev	Td	It will be about this long.	

Appendix K-5 : The activity chart of model construction task for design episode D



Appendix K-6 : The activity chart of design development task for design episode D



Appendix L: The questionnaire for refining the recommendations for a CAID system

What is your profession?

- ☐ Industrial Designer
- ☐ Design Educator
- ☐ Software Designer / Engineer
- ☐ Other ____________________

How many years have you worked in this profession?

- ☐ Novice
- ☐ 1 - 3 years
- ☐ 4 - 6 years
- ☐ More than 7 years

Which CAID system do you use or develop?

- ☐ Alias
- ☐ Auto-CAD
- ☐ Catia
- ☐ Ideas
- ☐ Microstation
- ☐ Pro-Engineer
- ☐ Solid Edge
- ☐ Solid work
- ☐ Others ____________

In the following question please indicate on the scale from –3 to 3 your degree of agreement or disagreement.

1. Do you agree that the free hand drawing is still an important tool for an industrial designer in the idea development stage?

	-3	-2	-1	0	1	2	3	
NO	☐	☐	☐	☐	☐	☐	☐	YES

Your Suggestions: ____

____

2. Do you agree that free hand drawing is more productive in the output of idea generation than using 2D-computer graphics software?

	-3	-2	-1	0	1	2	3	
NO	☐	☐	☐	☐	☐	☐	☐	YES

Your Suggestions: ____

____

____

3. Do you agree that 2D-computer graphics software is more suitable for the initial idea refining stage in industrial design?

	-3	-2	-1	0	1	2	3	
NO	☐	☐	☐	☐	☐	☐	☐	YES

Your Suggestions: ____

____

____

4. Do you agree that 3D software is not suitable for idea generation?

	-3	-2	-1	0	1	2	3	
NO	☐	☐	☐	☐	☐	☐	☐	YES

Your Suggestions: ____

____

____

5. Do you agree that 3D modelling software is more often applied in the final refining stage of industrial design?

	-3	-2	-1	0	1	2	3	
NO	☐	☐	☐	☐	☐	☐	☐	YES

Your Suggestions: ______________________________

____

____

6. Do you agree that when an industrial designer uses 3D modelling software, two activities: model construction and design development (refinement) take place?

	-3	-2	-1	0	1	2	3	
NO	☐	☐	☐	☐	☐	☐	☐	YES

Your Suggestions: ______________________________

____

____

7. If free hand drawing can be combined with 2D computer graphics and 3D modelling software in a single CAID system, do you agree that it would help industrial designers deal with design problems?

	-3	-2	-1	0	1	2	3	
NO	☐	☐	☐	☐	☐	☐	☐	YES

Your Suggestions: ______________________________

____

____

8. Do you agree that there should be a single common file format for all 3D CAID systems?

	-3	-2	-1	0	1	2	3	
NO	☐	☐	☐	☐	☐	☐	☐	YES

Your Suggestions: ______________________________

____

____

9. Do you agree that because experienced and junior designers (computer operators) are different in terms of professional experience and skills, future CAID system should offer two versions: one for the novice and the other for the expert, but be based on the same fundamental operation, graphics and commands?

	-3	-2	-1	0	1	2	3	
NO	☐	☐	☐	☐	☐	☐	☐	YES

Your Suggestions: ______________________________

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____

10. Do you agree that the 3D modelling software needs to provide computer algorithms, shape grammar, or a database to generate alternative solutions from an initial 3D-model design solution?

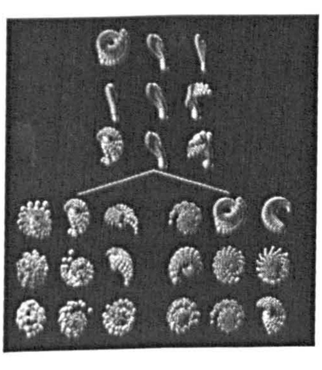
	-3	-2	-1	0	1	2	3	
NO	☐	☐	☐	☐	☐	☐	☐	YES

Your Suggestions: ______________________________

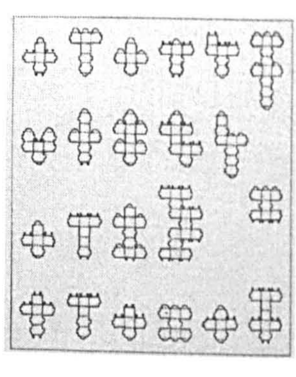
____

____

A sample of algorithms



A sample of shape grammar



11. Do you agree that future CAID systems should have a built in Artificial Intelligence (AI) to learn designers' modelling techniques and thus provide an automatic advice and support system?

	-3	-2	-1	0	1	2	3	
NO	☐	☐	☐	☐	☐	☐	☐	YES

Your Suggestions: ____

____

____

12. Do you agree that CAID system should also provide design methods support such as problem reduction, problem expansion, and problem digression to help industrial designer to explore possible solutions in initial design stage?

	-3	-2	-1	0	1	2	3	
NO	☐	☐	☐	☐	☐	☐	☐	YES

Your Suggestions: ____

____

____

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Appendix M: The raw material of questionnaire for evaluation of conclusions
Subjective 01: Winax Enterprise Co.

What is your profession?
Ans: Industrial Designer

How many years have worked in this profession?
Ans: More than 7 years

Which CAID system do you use or develop?
Ans: Auto-CAD
Pro-Engineer

1. Do you agree that the free hand drawing is still an important tool for an industrial designer in the idea development stage?
   Ans: 2
   Suggestions: None

2. Do you agree that free hand drawing is more productive in output of idea generation comparing to 2D computer graphics software using?
   Ans: 3
   Suggestions: The free hand sketch is the best way to explore new solutions for design problems. The 2D software restraints the designer's creativity in freedom.

3. Do you agree that 2D-computer graphics software using is more suitable for the initial idea refining stage in industrial design?
   Ans: 0
   Suggestions: Depending on How designers familiar with the 2D software. With scanning the sketches as a reference image into 2D software the designer will easier to improve their ideas.

4. Do you agree that 3D software is not suitable for idea generation?
   Ans: 2
   Suggestion: The present 3D software is not designed to perform idea generation in design development.

5. Do you agree that 3D modelling software is often applied at the final refining stage in industrial design?
   Ans: 3
   Suggestions: I think that it will be good for design projects, if the designer has the right concepts to work on 3D-model construction with 2D drawings.

6. Do you think during the time of industrial designer using 3D modelling software, two activities: model construction and design development (refinement) could be happen?
   Ans: 3
   Suggestions: If the designer is expert to the 3D computer software, he treats the detailed of product form with deliberation.

7. If the free hand drawing can be combined with the 2D computer graphics and 3D modelling software into a CAID system, do you think that it will help industrial designers to deal with the design problems?
   Ans: 3
   Suggestion: That must give a help to designer. I think that the most important factor is the designer's creativity and imagination.

8. Do you agree that there should be a single common file format for all 3D CAID systems?
Ans: 3
Suggestions: At the present the IGS format has been the normal one for several 3D-software packages. One format is a perfect version for the file transformation.

9. Do you agree that because experienced and junior designers (computer operators) are different in terms of professional experience and skills, future CAID system should offer two versions: one for the novice and the other for the expert, but be based on the same fundamental operation, graphics and commands?
Ans: -2
Suggestions: That means the price of the computer software will be higher.

10. Do you agree that the 3D modelling software needs to work with an algorithm system to generate alternative solutions to industrial design as the references 3D models for design problems?
Ans: -3
Suggestions: The system will interrupt and restraint designer's creativity.

11. Do you agree that future CAID systems should have a built in Artificial Intelligence (AI) to learn designers' modelling techniques and thus provide an automatic advice and support system?
Ans: 3
Suggestions: The most difficulty in 3D-model construction is that designer does not sure his construction method wither success on a complex curve form.

12. Do you agree that CAID system should also provide design methods support such as problem reduction, problem expansion, and problem digression to help industrial designer to explore possible solutions in initial design stage?
Ans: 1
Suggestions: This seems is not a bad idea. But I am not sure that this manner will help or stop designer's creativity in idea generation stage.

Appendix M: The raw material of questionnaire for evaluation of conclusions

Subjective 02: Alias/wavefront Inc.

What is your profession?
Ans: Software engineer

How many years have worked in this profession?
Ans: more than 7 years

Which CAID system do you use or develop?
Ans: Aias

1. Do you agree that the free hand drawing is still an important tool for an industrial designer in the idea development stage?
   Ans: 3
   Suggestions: This remains an important part of the design process even if it is digital sketching.

2. Do you agree that free hand drawing is more productive in output of idea generation comparing to 2D computer graphics software using?
   Ans: 3
   Suggestions: This is dependent on the user of the software and the software. The interface between the two is also very important.

3. Do you agree that 2D-computer graphics software using is more suitable for the initial idea refining stage in industrial design?
   Ans: 1
   Suggestions: It is only more suitable if you are in the office or have access to a computer. The term fag packet sketches springs to mind.

4. Do you agree that 3D software is not suitable for idea generation?
   Ans: 0
   Suggestion: I am not sure if it is used in the proper way then yes it is suitable of however you use it to create fully detailed ideas in 3D it can be unsuitable.

5. Do you agree that 3D modelling software is often applied at the final refining stage in industrial design?
   Ans: 2
   Suggestions: It is often the case as users can see in more detail the model they have created.

6. Do you think during the time of industrial designer using 3D modelling software, two activities: model construction and design development (refinement) could be happen?
   Ans: 1
   Suggestions: It can often be that to make the design the refine the design to make it easier to model.

7. If the free hand drawing can be combined with the 2D computer graphics and 3D modelling software into a CAID system, do you think that it will help industrial designers to deal with the design problems?
   Ans: 3
   Suggestion: Used at the initial stages of the design process this can help.

8. Do you agree that there should be a single common file format for all 3D CAID systems?
Ans: -2
Suggestions: This would be nice but it is nearly impossible in the commercial. All systems have many years' development and a standard format would be good for one but not another.

9. Do you agree that because experienced and junior designers (computer operators) are different in terms of professional experience and skills, future CAID system should offer two versions: one for the novice and the other for the expert, but be based on the same fundamental operation, graphics and commands?
Ans: 3
Suggestions: none

10. Do you agree that the 3D modelling software needs to work with an algorithm system to generate alternative solutions to industrial design as the references 3D models for design problems?
Ans: 3
Suggestions: none

11. Do you agree that future CAID systems should have a built in Artificial Intelligence (AI) to learn designers' modelling techniques and thus provide an automatic advice and support system?
Ans: 3
Suggestions: Sound great.

12. Do you agree that CAID system should also provide design methods support such as problem reduction, problem expansion, and problem digression to help industrial designer to explore possible solutions in initial design stage?
Ans: 3
Suggestions: none

Appendix M: The raw material of questionnaire for *evaluation of conclusions*

Subjective 03: RPD design

What is your profession?
Ans: Industrial designer

How many years have worked in this profession?
Ans: More than 7 years

Which CAID system do you use or develop?
Ans: Auto-CAD and Cadkey

1. Do you agree that the free hand drawing is still an important tool for an industrial designer in the idea development stage?
   Ans: 3
   Suggestions: The first conceptual designs should be initiated on paper, as in my opinion, it is very much easier for the brain to flow, rather than it having to deal with the vagaries of a CAD system at the same time.

2. Do you agree that free hand drawing is more productive in output of idea generation comparing to 2D computer graphics software using?
   Ans: 2
   Suggestions: Conceptual ideas can be put on paper much quicker and can be done anywhere.

3. Do you agree that 2D-computer graphics software using is more suitable for the initial idea refining stage in industrial design?
   Ans: -3
   Suggestions: After initial conceptual designs on paper, it is much easier to go 3D graphics of either solid modelling or surface.

4. Do you agree that 3D software is not suitable for idea generation?
   Ans: 3
   Suggestion: 3D software is ideal for secondary conceptual design generation, as it is then much easier to manipulate and reiterate your thoughts.

.

5. Do you agree that 3D modelling software is often applied at the final refining stage in industrial design?
   Ans: -1
   Suggestions: 3D modelling, such as, Alias and Catia tend to be used from the second stage onwards, as they are ideal products for moving designs along. Products, such as, Pro Engineer, are more engineering based and tend to be used in the latter stages of design for manufacturing purposes. These products are at the high cost end of the market and tend to be used in larger companies, whereas products, such as, Solid Edge and Solid Works are in the mid range and tend to be used by small to medium sized companies.

6. Do you think during the time of industrial designer using 3D modelling software, two activities: model construction and design development (refinement) could be happen?
   Ans: 2
   Suggestions: From the second stage of conceptual design, it is much easier with 3D design software to push model construction and design development along, as the reiterative processes that are required in design can be readily achieved.

7. If the free hand drawing can be combined with the 2D computer graphics and 3D modelling software into a CAID system, do you think that it will help industrial designers to deal with the design problems?
   Ans: 3
   Suggestion: If it was at all possible that you could scan easily a conceptual design on paper and import it into a 3D package, and easily manipulate it, this would be quite useful, but at present, I believe it still quite difficult.

8. Do you agree that there should be a single common file format for all 3D CAID systems?
   Ans: 3
   Suggestions: STEP and STL file systems are used more readily for this purpose these days.

9. Do you agree that because experienced and junior designers (computer operators) are different in terms of professional experience and skills, future CAID system should offer two versions: one for the novice and the other for the expert, but be based on the same fundamental operation, graphics and commands?
   Ans: 0
   Suggestions: Most of the larger CAD software suppliers are now selling on a two price basis under slightly different names, but this is generally so that they can get into large companies with the higher cost and small to medium companies with the lower cost. This could in effect be used to train junior and senior designers, as the lower cost software and skills are transferable across to the higher cost systems.

10. Do you agree that the 3D modelling software needs to work with an algorithm system to generate alternative solutions to industrial design as the references 3D models for design problems?
    Ans: 2
    Suggestions: A number of high-end CAD software have this type of arrangement already, but it is in its infancy.

11. Do you agree that future CAID systems should have a built in Artificial Intelligence (AI) to learn designers' modelling techniques and thus provide an automatic advice and support system?
    Ans: 1
    Suggestions: This is again starting to happen.

12. Do you agree that CAID system should also provide design methods support such as problem reduction, problem expansion, and problem digression to help industrial designer to explore possible solutions in initial design stage?
    Ans: 1
    Suggestions: This could be useful but with lazy designers could create bad design.

Appendix M: The raw material of questionnaire for evaluation of conclusions

Subjective 04: Design Unit in DMU

What is your profession?
Ans: Industrial designer / design educator

How many years have worked in this profession?
Ans: 4-6 years

Which CAID system do you use or develop?
Ans: Ideas and Microstation

1. Do you agree that the free hand drawing is still an important tool for an industrial designer in the idea development stage?
   Ans: 3
   Suggestions: none

2. Do you agree that free hand drawing is more productive in output of idea generation comparing to 2D computer graphics software using?
   Ans: 2
   Suggestions: People are inhibited by the software – thus less production.

3. Do you agree that 2D-computer graphics software using is more suitable for the initial idea refining stage in industrial design?
   Ans: 1
   Suggestions: none

4. Do you agree that 3D software is not suitable for idea generation?
   Ans: /
   Suggestion: /

5. Do you agree that 3D modelling software is often applied at the final refining stage in industrial design?
   Ans: 2
   Suggestions: none

6. Do you think during the time of industrial designer using 3D modelling software, two activities: model construction and design development (refinement) could be happen?
   Ans: 2
   Suggestions: none

7. If the free hand drawing can be combined with the 2D computer graphics and 3D modelling software into a CAID system, do you think that it will help industrial designers to deal with the design problems?
   Ans: 3
   Suggestion: none

8. Do you agree that there should be a single common file format for all 3D CAID systems?
Ans: /

Suggestions: /

9. Do you agree that because experienced and junior designers (computer operators) are different in terms of professional experience and skills, future CAID system should offer two versions: one for the novice and the other for the expert, but be based on the same fundamental operation, graphics and commands?
Ans: -1
Suggestions: Time spent learning is much less than time spent using the software rather see development on a "better" modelling package.

10. Do you agree that the 3D modelling software needs to work with an algorithm system to generate alternative solutions to industrial design as the references 3D models for design problems?
Ans: 1
Suggestions: none

11. Do you agree that future CAID systems should have a built in Artificial Intelligence (AI) to learn designers' modelling techniques and thus provide an automatic advice and support system?
Ans: 2
Suggestions: none

12. Do you agree that CAID system should also provide design methods support such as problem reduction, problem expansion, and problem digression to help industrial designer to explore possible solutions in initial design stage?
Ans: 0
Suggestions:

Appendix M: The raw material of questionnaire for evaluation of conclusions

Subjective 05: Design Unit in DMU

What is your profession?
Ans: Industrial designer

How many years have worked in this profession?
Ans: 4-6 years

Which CAID system do you use or develop?
Ans: Vellum Solids

1. Do you agree that the free hand drawing is still an important tool for an industrial designer in the idea development stage?
   Ans: 3
   Suggestions: none

2. Do you agree that free hand drawing is more productive in output of idea generation comparing to 2D computer graphics software using?
   Ans: 0
   Suggestions: Combination of freehand drawings and computer software 50%-50% for idea generation is best

3. Do you agree that 2D-computer graphics software using is more suitable for the initial idea refining stage in industrial design?
   Ans: 2
   Suggestions: none

4. Do you agree that 3D software is not suitable for idea generation?
   Ans: /
   Suggestion: /

5. Do you agree that 3D modelling software is often applied at the final refining stage in industrial design?
   Ans: 2
   Suggestions: none

6. Do you think during the time of industrial designer using 3D modelling software, two activities: model construction and design development (refinement) could be happen?
   Ans: /
   Suggestions: /

7. If the free hand drawing can be combined with the 2D computer graphics and 3D modelling software into a CAID system, do you think that it will help industrial designers to deal with the design problems?
   Ans: 0
   Suggestion: none

8. Do you agree that there should be a single common file format for all 3D CAID systems?
   Ans: /
   Suggestions: /

9. Do you agree that because experienced and junior designers (computer operators) are different in terms of professional experience and skills, future CAID system should offer two versions: one for the novice and the other for the expert, but be based on the same fundamental operation, graphics and commands?
   Ans: 2
   Suggestions: Good ideas.

10. Do you agree that the 3D modelling software needs to work with an algorithm system to generate alternative solutions to industrial design as the references 3D models for design problems?
    Ans: 3
    Suggestions: none

11. Do you agree that future CAID systems should have a built in Artificial Intelligence (AI) to learn designers' modelling techniques and thus provide an automatic advice and support system?
    Ans: 0
    Suggestions: Not too sure about that...

12. Do you agree that CAID system should also provide design methods support such as problem reduction, problem expansion, and problem digression to help industrial designer to explore possible solutions in initial design stage?
    Ans: 0
    Suggestions: none

Appendix M: The raw material of questionnaire for evaluation of conclusions
Subjective 06: Design Unit in DMU

What is your profession?
Ans: Industrial designer / design educator

How many years have worked in this profession?
Ans: More than 7 years

Which CAID system do you use or develop?
Ans: Ideas, Microstation and Solid Edge

1. Do you agree that the free hand drawing is still an important tool for an industrial designer in the idea development stage?
   Ans: 3
   Suggestions: An ability to draw in 3D is a good indicator of a 3D mind. At the end of the day we are designing 3D artefacts for 3D people in a 3D area.

2. Do you agree that free hand drawing is more productive in output of idea generation comparing to 2D computer graphics software using?
   Ans: 3
   Suggestions: Same reason as Q4.

3. Do you agree that 2D-computer graphics software using is more suitable for the initial idea refining stage in industrial design?
   Ans: 0
   Suggestions: Needs a combination of 2D hand, 2D CAD and 3D CAD.

4. Do you agree that 3D software is not suitable for idea generation?
   Ans: /
   Suggestion: /

5. Do you agree that 3D modelling software is often applied at the final refining stage in industrial design?
   Ans: -2
   Suggestions: I don't.

6. Do you think during the time of industrial designer using 3D modelling software, two activities: model construction and design development (refinement) could be happen?
   Ans: 3
   Suggestions: And the rest.

7. If the free hand drawing can be combined with the 2D computer graphics and 3D modelling software into a CAID system, do you think that it will help industrial designers to deal with the design problems?
   Ans: -3
   Suggestion: You need a break from the computer and it is faster for a group of people to get around a piece of paper.

8. Do you agree that there should be a single common file format for all 3D CAID systems?
Ans: /

Suggestions: /

9. Do you agree that because experienced and junior designers (computer operators) are different in terms of professional experience and skills, future CAID system should offer two versions: one for the novice and the other for the expert, but be based on the same fundamental operation, graphics and commands?
Ans: 0
Suggestions: Only if in providing a novice ability it does not compromise the expert, as does Solid Edge / Solid Works.

10. Do you agree that the 3D modelling software needs to work with an algorithm system to generate alternative solutions to industrial design as the references 3D models for design problems?
Ans: 0
Suggestions: Only if the industrial designer is weak or inexperienced.

11. Do you agree that future CAID systems should have a built in Artificial Intelligence (AI) to learn designers' modelling techniques and thus provide an automatic advice and support system?
Ans: 0
Suggestions: possibly

12. Do you agree that CAID system should also provide design methods support such as problem reduction, problem expansion, and problem digression to help industrial designer to explore possible solutions in initial design stage?
Ans: -3
Suggestions: Because design problems can be very different and should not be tackled by formula. This would be dangerous and potentially restrict creativity.

Appendix M: The raw material of questionnaire for evaluation of conclusions

Subjective 07: Polaroid USA

What is your profession?
Ans: new product development designer

How many years have worked in this profession?
Ans: More than 7 years

Which CAID system do you use or develop?
Ans: Pro-engineer and solid work

1. Do you agree that the free hand drawing is still an important tool for an industrial designer in the idea development stage?
   Ans: 3
   Suggestions: Hand drawing is a quick tool to communicate ideas at the concept stage.

2. Do you agree that free hand drawing is more productive in output of idea generation comparing to 2D computer graphics software using?
   Ans: 1
   Suggestions: None

3. Do you agree that 2D-computer graphics software using is more suitable for the initial idea refining stage in industrial design?
   Ans: -1
   Suggestions: If it is possible, I'd like to skip 2D graphics and go straight to 3D modelling and rapid prototyping.

4. Do you agree that 3D software is not suitable for idea generation?
   Ans: -2
   Suggestion: It takes longer to model the ideas, but sometimes it communicates ideas better, and shortens the evaluation process.

5. Do you agree that 3D modelling software is often applied at the final refining stage in industrial design?
   Ans: 3
   Suggestions: none

6. Do you think during the time of industrial designer using 3D modelling software, two activities: model construction and design development (refinement) could be happen?
   Ans: 2
   Suggestions: none

7. If the free hand drawing can be combined with the 2D computer graphics and 3D modelling software into a CAID system, do you think that it will help industrial designers to deal with the design problems?
   Ans: 3
   Suggestion: If the system were simple to use, it would be beneficial to designers.

8. Do you agree that there should be a single common file format for all 3D CAID systems?
Ans: 3
Suggestions: Ideally, yes.

9. Do you agree that because experienced and junior designers (computer operators) are different in terms of professional experience and skills, future CAID system should offer two versions: one for the novice and the other for the expert, but be based on the same fundamental operation, graphics and commands?
Ans: -3
Suggestions: Tools shouldn't be a limitation to anyone to do their jobs, unless there is a huge different in price of the CAID systems (economical benefits for corporations).

10. Do you agree that the 3D modelling software needs to work with an algorithm system to generate alternative solutions to industrial design as the references 3D models for design problems?
Ans: 0
Suggestions: none

11. Do you agree that future CAID systems should have a built in Artificial Intelligence (AI) to learn designers' modelling techniques and thus provide an automatic advice and support system?
Ans: 1
Suggestions: If the system helps designers do their jobs faster and more efficient way.

12. Do you agree that CAID system should also provide design methods support such as problem reduction, problem expansion, and problem digression to help industrial designer to explore possible solutions in initial design stage?
Ans: 0
Suggestions: none

Appendix M: The raw material of questionnaire for evaluation of conclusions

Subjective 08: Sampo Co.

What is your profession?
Ans: Industrial designer

How many years have worked in this profession?
Ans: More than 7 years

Which CAID system do you use or develop?
Ans: Ideas

1. Do you agree that the free hand drawing is still an important tool for an industrial designer in the idea development stage?
   Ans: 3
   Suggestions: So far, there are still no such a software which can let designer record the path of their thinking as fast and effective as hand drawings.

2. Do you agree that free hand drawing is more productive in output of idea generation comparing to 2D computer graphics software using?
   Ans: 3
   Suggestions: None

3. Do you agree that 2D-computer graphics software using is more suitable for the initial idea refining stage in industrial design?
   Ans: 3
   Suggestions: I think it is faster and more effective than hand drawing and 3D software.

4. Do you agree that 3D software is not suitable for idea generation?
   Ans: 3
   Suggestion: It takes too much time for one idea, which will become a barrier for idea generation.

5. Do you agree that 3D modelling software is often applied at the final refining stage in industrial design?
   Ans: 3
   Suggestions: none

6. Do you think during the time of industrial designer using 3D modelling software, two activities: model construction and design development (refinement) could be happen?
   Ans: 2
   Suggestions: none

7. If the free hand drawing can be combined with the 2D computer graphics and 3D modelling software into a CAID system, do you think that it will help industrial designers to deal with the design problems?
   Ans: 3
   Suggestion: none

8. Do you agree that there should be a single common file format for all 3D CAID systems?
Ans: 3
Suggestions: none

9. Do you agree that because experienced and junior designers (computer operators) are different in terms of professional experience and skills, future CAID system should offer two versions: one for the novice and the other for the expert, but be based on the same fundamental operation, graphics and commands?
Ans: 3
Suggestions: none

10. Do you agree that the 3D modelling software needs to work with an algorithm system to generate alternative solutions to industrial design as the references 3D models for design problems?
Ans: 3
Suggestions: none

11. Do you agree that future CAID systems should have a built in Artificial Intelligence (AI) to learn designers' modelling techniques and thus provide an automatic advice and support system?
Ans: 3
Suggestions: This AI system will be able to perform some routine jobs and thus effectively enhance the designers' efficiency.

12. Do you agree that CAID system should also provide design methods support such as problem reduction, problem expansion, and problem digression to help industrial designer to explore possible solutions in initial design stage?
Ans: 3
Suggestions: none